

IMPERIAL COLLEGE LONDON

Department of Mechanical Engineering

Dissertation

**Development of a novel Fast light Alloy Stamping
Technology (FAST) for manufacturing lightweight
panel components using high strength aluminium
alloys: Experimental studies**

By

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Diploma of Membership of Imperial College London

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Declaration of originality

I, XI LUAN, declare that the work presented in this thesis titled ‘Development of a novel Fast light Alloy Stamping Technology (FAST) for manufacturing lightweight panel components using high strength aluminium alloys: Experimental studies’ is my own, and that any work that is not has been referenced appropriately.

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Abstract

This study focuses on the development of a novel sheet metal forming process, Fast light Alloy Stamping Technology (FAST), for manufacturing aluminium alloy sheet components through experimental studies. This novel process is distinguished by an ultra-fast heating rate during the heating stage and precision processing parameters control in order to minimize changes to the material microstructure which are detrimental to the post-form strength. As the initial temper and the pre-existing hardening phases of the material could be maintained throughout the heating and stamping stages, the paint bake cycles utilized by different automakers are sufficient for the material to attain its full strength, replacing the need of post-form artificial ageing. The forming temperature selection for the process therefore depends only on the level of formability required, further reducing the energy consumption and cycle time of the process.

The proof-of-concept and the mechanism of FAST were studied through a series of the heat treatment tests using the aluminium alloy AA6082 in naturally aged T4 temper and artificially aged T6 temper. Traditional warm and hot stamping processes in which the specimens were heated at a slow heating rate were conducted at the identical forming temperature range as a comparison. It has been proved that the post-form strength of the specimen after the FAST process and paint bake cycles could achieve 112 Hv, more than 95% of the as-delivered T6 condition. In addition, the thermal-mechanical properties of the material under the ultra-fast heating conditions were investigated using the Gleeble 3800 thermal-mechanical simulator. The true fracture strain was as high as 0.85 at 450°C for both materials and over 0.50 and 0.32 at 300°C for the AA6082-T4 and T6 respectively.

A dedicated pilot production line Uni-Form for the FAST process was designed, fabricated and used for conducting the forming tests. As a highly integrated test facility, Uni-Form is able to conduct the forming trials in an automated manner. In this work, a U-shape forming tool was utilized to enable the study of mechanical properties of the FAST formed components. The influence of forming temperature and forming speed on the springback was investigated. The post-form strength and the surface roughness of the formed components were examined. Furthermore, a benchmark study on the manufacturing cycle time was carried out. It was determined that FAST is able to reduce the manufacturing cycle time to less than 8.5 seconds

to produce the component with the desired mechanical properties from the metal blank, which is only 4.3% of the warm forming process time currently used in the automotive industry. The experimental forming trials confirmed that the FAST process can be scaled up to a forming process in industry for manufacturing the lightweight stampings with the required strength and geometrical accuracy.

With the advantages of the FAST process presented in this study, further investigation of this novel forming technology could be conducted in order to expand its application to other types of heat treatable aluminium alloys and the tailor welded blanks of different series aluminium alloys.

Acknowledgements

To my beloved grandpapa.

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Nomenclature

<i>3D</i>	Three-dimension
<i>3DAP</i>	Three-dimension atom probe
<i>AA</i>	Aluminium alloy
<i>BIW</i>	Body-in-White
<i>C</i>	Computer program of the Uni-Form
<i>CRSS</i>	Critical resolved shear stress
<i>D</i>	The thermocouple & data logger
<i>DIC</i>	Digital image correlation
<i>DSC</i>	Differential scanning calorimetry
<i>EBSD</i>	Electron back-scattered diffraction
<i>HFQ</i>	Solution heat treatment, forming and cold-die quenching
<i>HRTEM</i>	High resolution transmission electron microscopy
<i>HV</i>	Vickers hardness
<i>L</i>	Literatures
<i>LCA</i>	Life cycle assessment
<i>NA</i>	Not applicable
<i>P</i>	Gas spring pressure
<i>PAS</i>	Positron annihilation spectroscopy
<i>PBR</i>	Paint bake response
<i>PLC</i>	Portevin-Le Chatelier effect
<i>P&B</i>	Paint and bake
<i>P&B A</i>	Paint and bake schemes A
<i>P&B B</i>	Paint and bake schemes B
<i>QPF</i>	Quick plastic forming
<i>r</i>	Radius of the particle
<i>R</i>	Die / Punch radius
<i>Ra</i>	Surface roughness

<i>RT</i>	Room temperatrue
<i>SHT</i>	Solution heat treatment
<i>SPF</i>	Superplastic forming
<i>SSSS</i>	Supersaturated solid solution
<i>t</i>	Time / Duration
<i>t_{An}</i>	Artificial ageing time
<i>t_f</i>	Forming time of the forming process in the cycle time study
<i>t_{f&q}</i>	Forming and quenching time of the forming process
<i>t_h</i>	Heat treatment time of the forming process in the cycle time study
<i>t_{heating}</i>	Heating time of the forming process
<i>t_n</i>	Natural ageing time
<i>t_p</i>	Post processing time of the forming process in the cycle time study
<i>t_{Sn}</i>	Room temperature storage time
<i>t_{soaking}</i>	Soaking time in the uniaxial tensile test
<i>t_{tensile test}</i>	Tensile to failure time in the uniaxial tensile test
<i>t_{tf}</i>	Specimen transfer time of the forming process
<i>T</i>	Temperature
<i>T_{ageing}</i>	Artificial ageing temperature
<i>T_{FAST}</i>	The forming temperature of the FAST process
<i>T_m</i>	Melting point of the material
<i>T_{RT}</i>	Room temperature
<i>T_{SHT}</i>	Solution heat treatment temperature of the material
<i>T_{Warm forming}</i>	Warm forming temperature
<i>$\dot{T}$</i>	Heating rate
<i>TEM</i>	Transmission electron microscopy
<i>UTS</i>	Ultimate tensile stress
<i>wt%</i>	Weight percentage

ε	Strain
$\dot{\varepsilon}$	Strain rate
θ_A	Flange springback angle
θ_B	Sidewall springback angle
σ	Stress / flow stress
$\sigma_{0.2}$	Flow stress at the strain level of 0.2
$\sigma(t)$	The yield stress of the material during the ageing process
σ_i	The intrinsic strength of pure aluminium
$\Delta\sigma_{bypassing}$	Strength due to precipitate bypassing
$\Delta\sigma_{ppt}$	Strength due to the precipitation hardening
$\Delta\sigma_{shearing}$	Strength due to precipitate shearing
$\Delta\sigma_{ss}$	Solid solution strength

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Chapter 1

Introduction

1.1 The automotive industry under new environmental regulations

In recent years, there has been an urgent need to produce vehicles with low carbon footprint owing to the environmental and political pressure (European Parliament, 2014). According to studies conducted by the European Commission (European Commission, 2017), the vehicle emissions have accounted for an estimated 12% of the total European Union (EU) carbon dioxide (CO_2) emission, which is approximately 425.8 million tonnes per year. In light of this, increasingly stringent environmental regulations for vehicles on the market have been established by successive governments. In 2015, the target of the average emission level of a new vehicle was 130 grams of CO_2 per kilometre (g/km), which is equivalent to a fuel consumption of 5.6 liters per one hundred kilometres (L/100km). In 2016, this target was revised to 118.1 g/km and 5.1 L/100km respectively, which is a marked decrease of 9.23% yearly. At present, the EU has set the target for the fleet average of all new vehicles belonging to one brand to 95 g/km CO_2 emissions and improve the fuel efficiency to 4.1 L/100km by 2021. Compared with the target ten years prior in 2007 at 158.7 g/km, this new target would lead to a reduction of over 40%. Furthermore, the government has simultaneously drawn up severe punitive measures for failing to meet these targets (European Parliament, 2009). For example, the manufacturer must pay penalty payments in terms of g/km for every new car registered when the fleet average of the CO_2 emission exceeds the target value after 2012. For the first gram of exceedance, the charge is €5 per car. For the second gram, €15 per car and for the third gram, €25 per car. For each subsequent gram the charge increases to €95 per car. This latter charge of €95/car was extended from the first gram after 2019 (European Parliament, 2009). Likewise in the United States of America, the Corporate Average Fuel Economy (CAFE) standards (NATSA, 2015) require the automakers to increase their fleet average fuel efficiency to 54.5 miles per gallon (mpg) by 2025, which is almost double the current value (The White House, 2010). The penalty in the United States of America is \$55 for each mpg under the

standard per registered vehicle at present and would increase to \$100 in the near future (Wood et al., 2018).

To this end, tremendous efforts have been made by vehicle manufacturers in adapting to the new fuel efficiency and emission standards, and new technologies applied to vehicles have been experiencing a remarkable growth. Compared with other technologies, such as hybrid propulsion technology (Amjad et al., 2010), small-displacement with turbo charging (Johnson and Joshi, 2017) and Battery Electric Vehicles (BEV) (Un-Noor et al., 2017), lightweighting, especially through the utilization of aluminium alloys to replace steels in vehicles, has become an efficient and popular approach of this process (Zheng et al., 2018 (a); Mallick, 2010). It has been proved that every 10% saving of the vehicle weight can lead to 5-7% increase of vehicle fuel efficiency without compromising the performance and safety (Lutsey, 2010). Moreover, according to the study of global aluminum alloy production, it is estimated that every tonne of steel replaced by aluminium alloy could enable approximately 18 tons of CO_2 reduction over the average service life of a midsize vehicle (Benedyk, 2010).

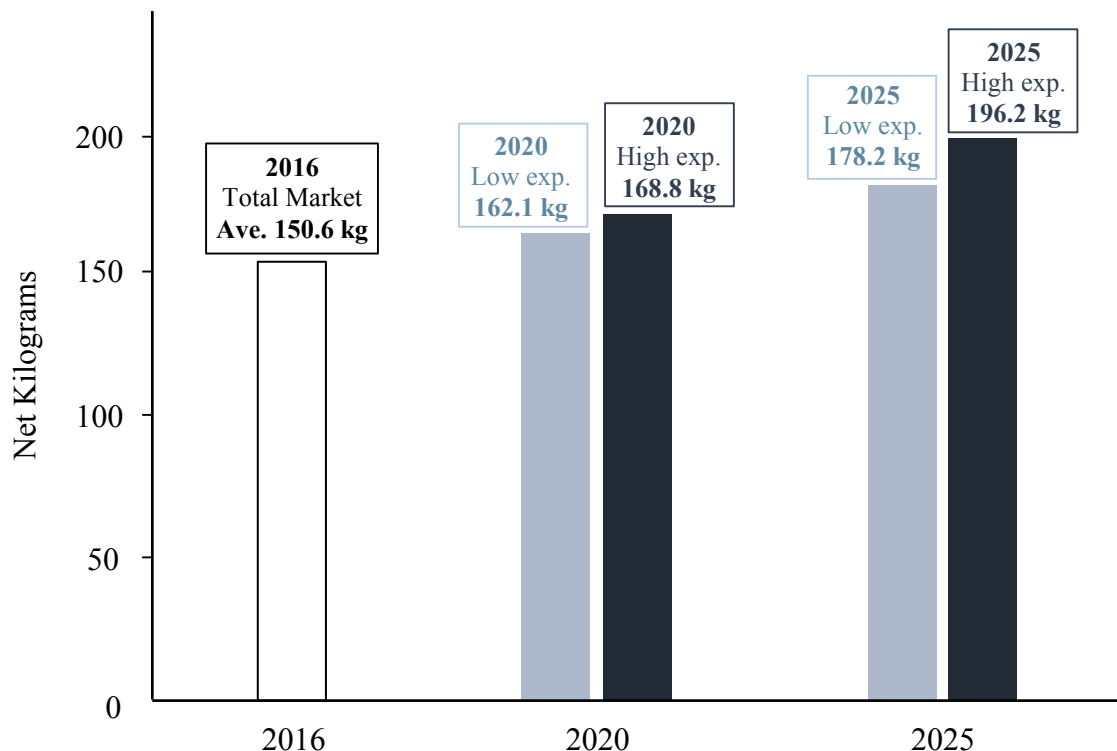


Fig 1.1 European Union light vehicle aluminium content current situation and low/high expectations (Net kilograms per vehicle) (Ducker Worldwide, 2016)

The report to the European Aluminium Association (EAA) by Ducker Worldwide (Figure 1.1) demonstrates that the utilization of aluminium alloys in European vehicles will continue to show an uninterrupted growth in the next decade (Ducker Worldwide, 2016). In the most optimistic scenarios, aluminium content per vehicle would grow to 170 kg in 2020 and 196 kg in 2025. The same trend can be found in the US market, as shown in Figure 1.2 (Ducker Worldwide, 2017). In addition, Ducker Worldwide predicted that more than 75% of pickup trucks and 20% of SUVs and large sedans produced in North America would be aluminum-bodied by 2025 (Ducker Worldwide, 2017).

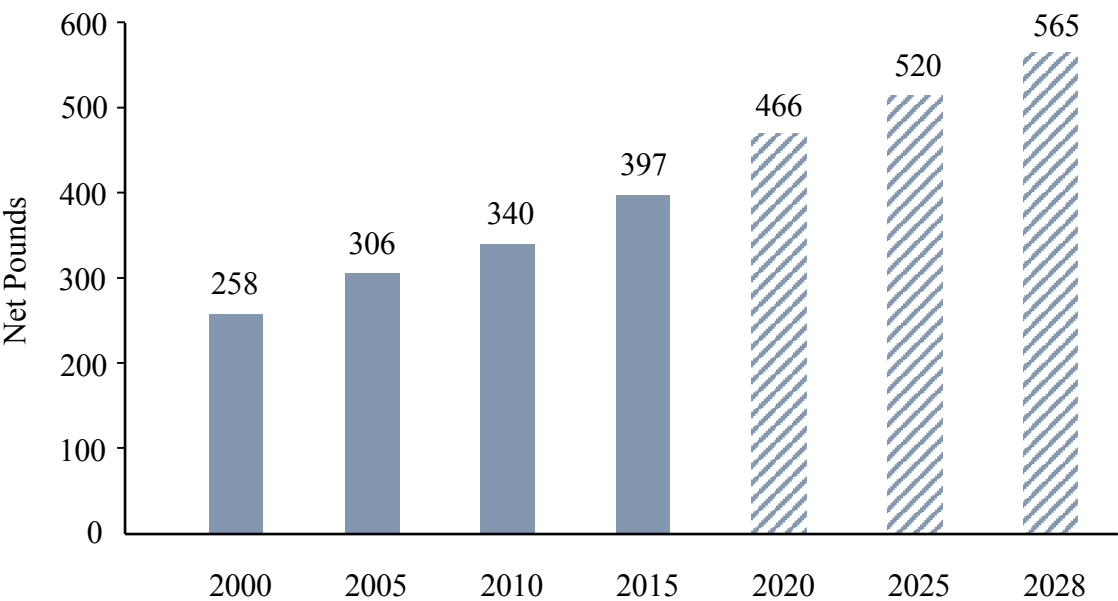


Fig 1.2 North American light vehicle aluminium content current situation and expectations (Net pounds per vehicle) (Ducker Worldwide, 2017)

1.2 Aluminium alloys for automotive applications

The utilization of aluminium alloys in vehicles can date back to the 1900s, when the world's first full aluminium bodied vehicle was produced by Karl Benz in 1899 (Bach, 2019). Nowadays, the aluminium alloys utilized in automobiles are far more diverse than other competitive materials such as steel, magnesium alloys and carbon fiber. This is mainly due to the high flexibility of the material, where aluminium alloys can be manufactured as either wrought or cast with the ability to be adaptable to almost all types of mechanical manufacturing processes (Kaufman, 2008).

Typical aluminium alloy applications and product forms in vehicles are demonstrated in Figure 1.3 (Mallick, 2010). In general, the product forms can be divided into three categories: casting, extrusion and sheet metal forming components. The aluminium alloy casting is normally used to produce wheels, engine blocks and pistons. Extrusion dominates the production of engine cradles, space frames and seat frames. Sheet metal forming is widely employed to manufacture the closure and body-in-white (BIW) components.

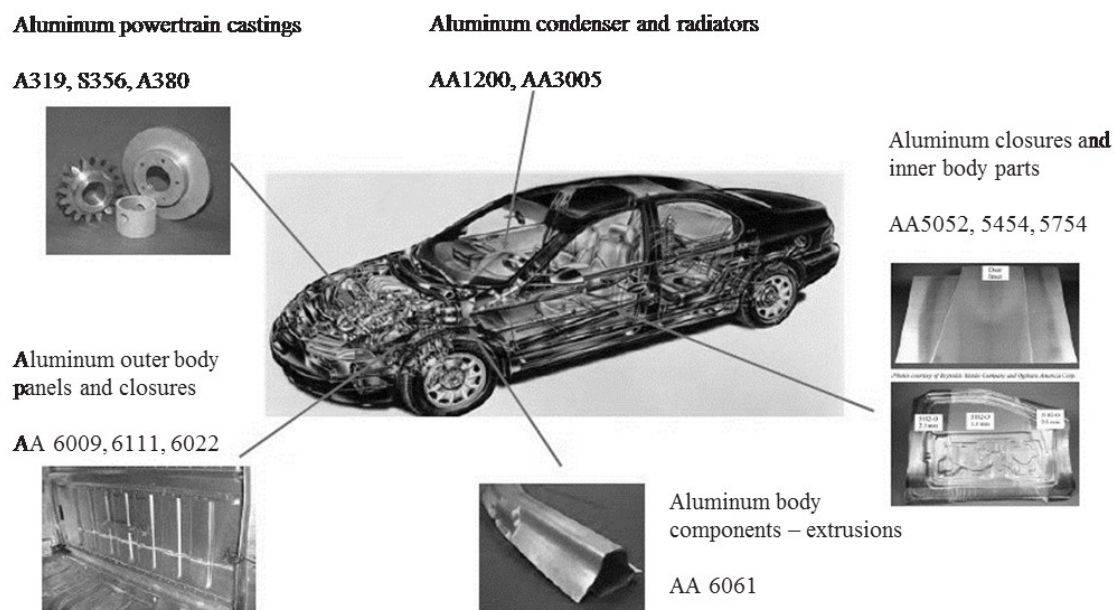


Fig 1.3 Typical vehicle aluminium alloy applications and product forms (Mallick, 2010)

According to a survey of thirty key components of a vehicle in 2016 and 2020 by Ducker in 2017 (Ducker Worldwide, 2017), the aluminium content manufactured by casting and extrusion would remain constant, whereas the sheet aluminium alloy components would experience a remarkable growth due to the increased penetration rate for body closures and body-in-white (BIW) components, as highlighted in Figure 1.4.

To be specific, the average aluminium content for closure components is believed to increase from 10.43 kg/vehicle in 2015 to 27.67 kg/vehicle in 2020, which equals to a 1.65 times increase in 5 years. The share of doors made by aluminium alloys would increase from under 5% in 2015 to more than 25% in 2020. Meanwhile, an increase of the aluminium hood would be from

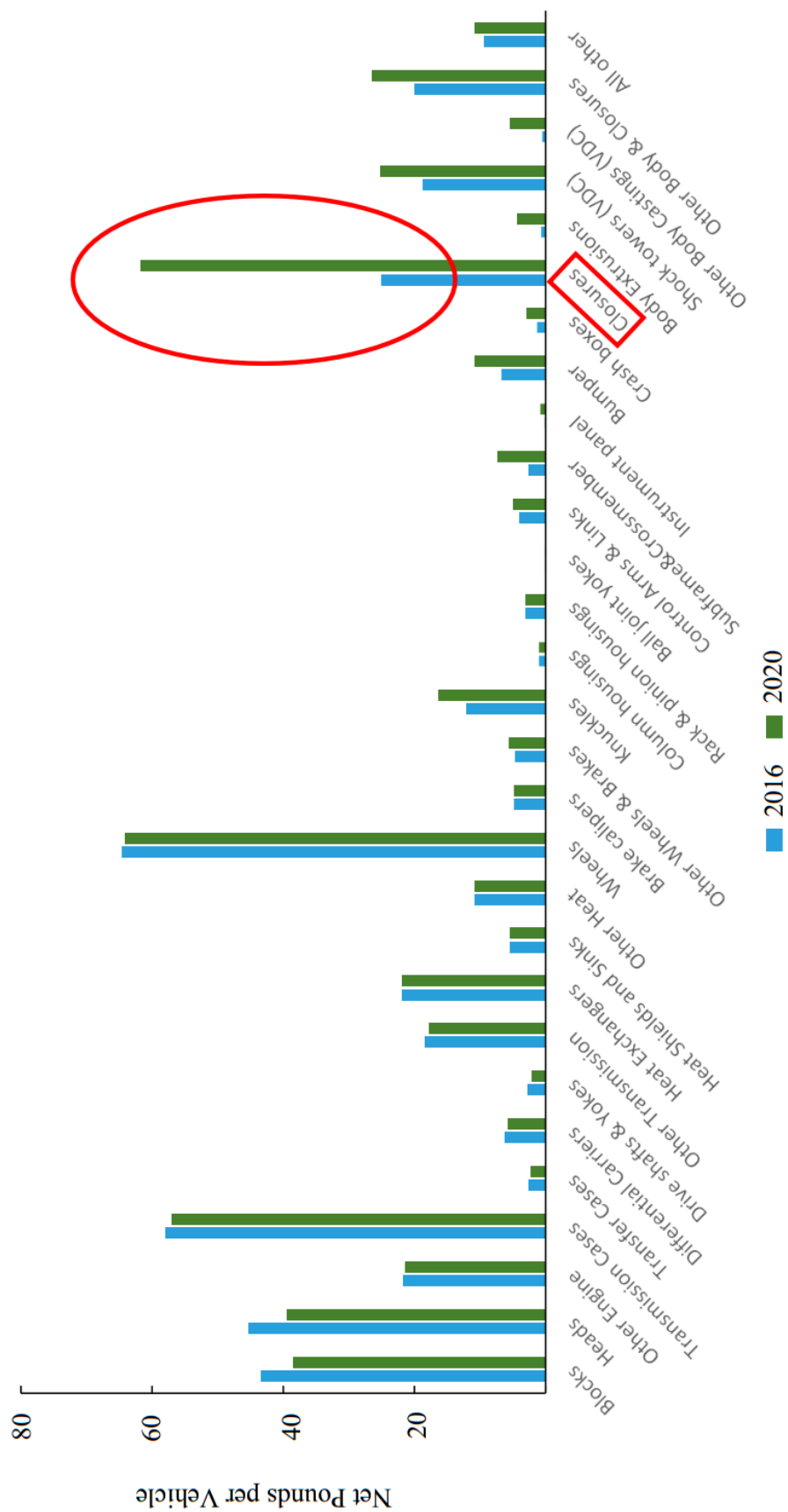


Fig 1.4 Vehicle aluminium content by key components and systems in 2016 and 2020 (Ducker Worldwide, 2017)

less than 50% in 2015 to slightly over 71% in 2020 (Ducker Worldwide, 2017). Concurrently, the average weight of body-in-white (BIW) components made by aluminium panels is expected to experience a growth from 6.35 kg/vehicle to 11.79 kg/vehicle from 2015 to 2020, which is an increase of 83%. In total, there would be at least 39.46 kg of sheet aluminium alloy components per vehicle by 2020. According to the global vehicle production volume at present, such a prospective scenario will equal to over 1 million tons of aluminium sheet manufactured by stamping annually and could increase to 1.1 million tons under an optimistic estimation (Ducker Worldwide, 2017; Butler Jr, 2015).

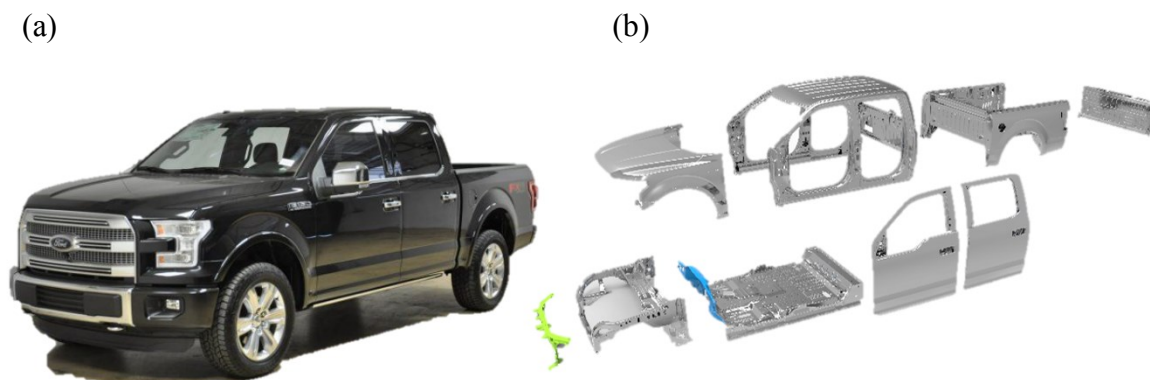


Fig 1.5 (a) Ford F-150 (the 13th generation); (b) The sheet aluminium alloy components used in Ford F-150 (Stacey, 2016)

One example demonstrating the trend to produce sheet aluminium alloy components in mass produced vehicles is the 13th generation Ford F-150 (2015-present), as shown in Figure 1.5 (a). Sports cars and high-end luxury cars such as Audi A8, Jaguar XJ and Range Rover have employed the full-aluminium body over the past two decades (Jaguar Land Rover, 2019; Ducker Worldwide, 2012). However, the Ford F-150 is the world's first high-volume family car, 909,330 sold in 2018 (Motrolix, 2019), which widely applies aluminium panels, as shown in Figure 1.5 (b). Compared with the predecessor, the new Ford F-150 saves more than 750 pounds (340 kg) in weight and increases fuel efficiency by over 21% from 19 mpg to 23 mpg (Ford Motor Company, 2019; Stacey, 2016).

1.3 Current sheet metal forming technologies for aluminium alloys

Despite the remarkable potential growth of aluminium alloys, particularly aluminium panel components in the automotive industry, the application of aluminium sheets is still restricted by their poor formability at ambient temperature (Hosford and Caddell, 2011) compared with low carbon steels, which can be cold formed and directly welded during assembly of the vehicle body-in-white (BIW) and without post-form heat treatments (Altan and Tekkaya, 2012 (a)).

Figure 1.6 summarizes the mechanical properties of several commonly used aluminium alloys (Kaufman, 2008). It can be found that total elongation to failure is normally within 20% and 12% for the medium and high strength aluminium alloys at ambient temperature respectively.

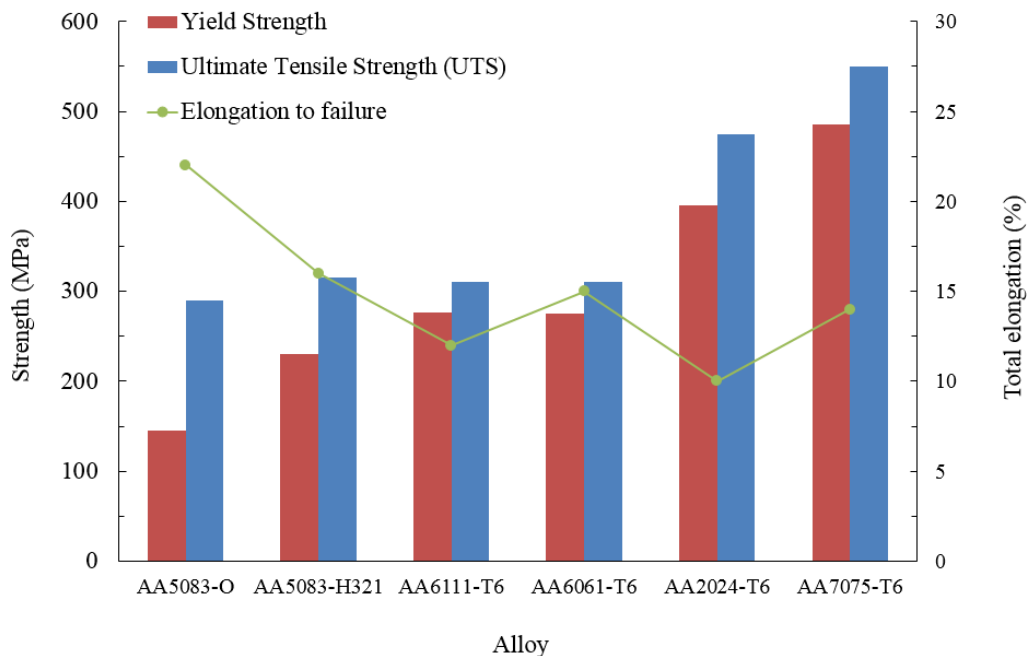


Fig 1.6 Comparisons of mechanical properties of commonly used aluminium alloys at ambient temperature (Kaufman, 2008)

In general, the most common technologies involve forming the alloys at elevated temperatures. Warm forming was first investigated by Finch et al. in 1946 (Finch et al., 1946). It was found that the drawability, in terms of cup height, could be improved for the aluminium alloys AA2024 and AA7075 at 150°C. Since this initial study, significant research has been performed into the elevated temperature forming of aluminium alloys. Cavaliere studied AA2618 and found the equivalent strain to failure was improved from 0.27 to 0.38 when the forming

temperature was increased from 150 °C to 250 °C at a strain rate of 1/s (Cavaliere, 2002). According to Li and Ghosh (2004), it was shown that the formability of the aluminium sheet alloys AA5754, AA5182+Mn and AA6111 formed at 250 °C, in terms of their strain states, were comparable to those of A-K steels formed at room temperature. Therefore, the warm forming process has been employed by several vehicle manufacturers for over a decade, such as Jaguar and Land Rover (Sheller, 2014). In the meantime, some limitations still exist in the warm stamping processes. Although the true fracture strain usually exhibits an improvement to around 0.27 once the forming temperature is greater than 250 °C (Mallick, 2010), the forming temperatures used in warm forming processes are usually kept below 300 °C. Since higher temperature tends to cause recovery (Verdier et al., 1998) and precipitate coarsening (Liao, 2014) of aluminium alloys, this leads to a decrease of the strength of the formed components. In addition, the blank is commonly heated by conduction using heated forming tools in warm forming processes, where electric heating rods are inserted into the die, punch and blank holder to heat up the blank, resulting in a complex apparatus and a long time to preheat the equipment (Altan and Tekkaya, 2012 (b)).

In addition to the warm forming processes, some hot forming technologies have also been developed (Garrett et al., 2005; Grohmann, 2016), where the aluminium sheet is heated to the solutionizing temperature for solution heat treatment, followed by forming and quenching simultaneously in the dies. Since all the constituents are fully dissolved into the aluminium matrix and the yield stress is significantly reduced, the material exhibits improved formability, enabling a more complex shape to be formed. However, the post-form strength of the formed component can only be regained by subsequent artificial ageing processes (Mohamed et al., 2012). It is worth noting that these hot forming processes have been successfully applied to the forming of some complex-shaped components such as a vehicle door inner panel (Politis et al., 2013). However, component with less complex geometries could benefit from the technologies that offer a shorter cycle time and reduced energy consumption.

1.4 Aim and objectives of this study

The aim of this research is to develop a new sheet metal forming technology for manufacturing sheet aluminium alloy components that meet the technical requirements for mass production in the automotive industry, such as moderate formability, high post-form strength, short cycle time

and minimal energy consumption. This new forming technology is proposed to utilize the ultra-fast heating rate to heat up the aluminium blank to elevated temperature. The novelty of this study lies in exploring the effects of heating rate and the temperature concurrently on the properties of the heat treatable aluminium alloy during the sheet metal forming process and developing the dedicated test facilities realizing this new forming technology. The work centres on aluminium alloy AA6082, which has witnessed a surge in scientific research and industrial application in recent years due to its high strength to weight ratio, good corrosion resistance and excellent precipitation hardening response during the ageing process (Polmear et al., 2017).

In order to achieve the aim of this study, the following objectives have to be fulfilled.

1. Conduct an in-depth, comprehensive literature review on the 6xxx series aluminium alloy and the existing forming technologies for aluminium alloys to understand the current scientific gaps on this material and the industrial needs on the formability, manufacturing cycle time, post-form strength and the state of the art of these technologies.
2. Based on the understanding of the material properties under elevated temperatures and the improvements of existing sheet metal forming technologies, propose a new forming technology for manufacturing lightweight panel components using high strength aluminium alloys.
3. Design and build dedicated test facilities to conduct the experiments and forming trials of the proposed forming process.
4. Design and carry out a comprehensive study on the proposed forming technology and investigate the underlying physical mechanism.
5. Conduct the forming trials using the dedicated test facility to study the mechanical properties of the formed components as well as the manufacturing cycle time using this new technology.

1.5 Thesis structure

This thesis is comprised of seven chapters. A flow diagram which clarifies the structure of this study is presented in Figure 1.7. A brief introduction of aluminium alloy usage, especially the sheet aluminium alloy components in vehicles is presented in Chapter 1. Chapter 2 serves as a

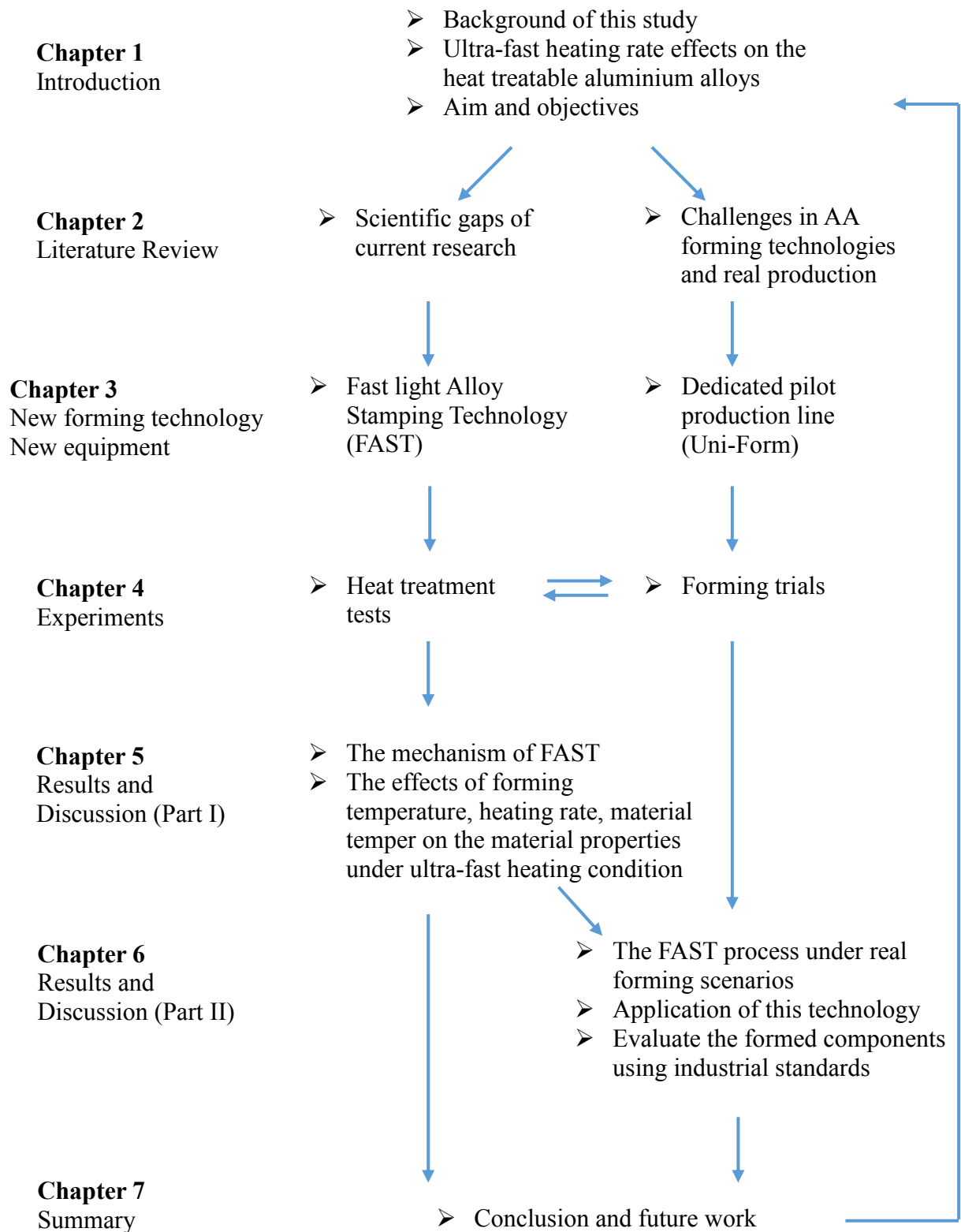


Fig 1.7 Flow diagram of the study

literature review. The material properties and precipitation hardening mechanism of Aluminium-Magnesium-Silicon (Al-Mg-Si, 6xxx series) alloy are summarized and the scientific gaps of the current research are identified. Meanwhile, the sheet metal forming technologies and the industrial needs for manufacturing sheet aluminium alloy components are discussed. In Chapter 3, the novel forming technology, Fast light Alloy Stamping Technology (FAST), is proposed. The development of the dedicated test facility Uni-Form is also demonstrated. Chapter 4 is dedicated to the experimental programme of the FAST process study with a series of tests designed and performed, covering the heat treatment tests of FAST and the forming trials using Uni-Form. Chapter 5 details the analysis of the experimental results. The effects of forming temperature and material temper on the FAST process are investigated. The thermo-mechanical properties of the material under ultra-fast heating conditions are also explored. Chapter 6 focuses on the forming trials of the FAST process using Uni-Form. A study of the formed components and a benchmark study on cycle time of the FAST process and other forming technologies are presented. Finally, Chapter 7 presents the conclusions of this study and the suggestions for the future work.

Chapter 2

A review on Aluminium-Magnesium-Silicon alloy and sheet metal forming technologies for aluminium alloys

2.1 Introduction

The Aluminium-Magnesium-Silicon (Al-Mg-Si, 6xxx series) alloy is one of the most widely used material candidates for manufacturing lightweight panel components in the automotive industry. In this chapter, the material properties and the applications of several types of Al-Mg-Si alloys including AA6082 and AA6111 are reviewed. The precipitation hardening mechanisms of the 6xxx series aluminium alloys including the precipitation sequence and the morphology of different precipitates are discussed. The modelling of the precipitation hardening process is also presented. Moreover, the state of the art in the field of sheet metal forming technologies for aluminium alloys is reviewed, covering the solution heat treatment, forming and cold-die quenching (HFQ), the superplastic forming (SPF) of aluminium alloys and the W-Temper forming processes. The development, the main stages, the materials that can be applied, improvements and limitations of these forming technologies are described and the industrial needs for manufacturing aluminium panel components are addressed.

2.2 Aluminium-Magnesium-Silicon (Al-Mg-Si) alloy and its precipitation hardening process

2.2.1 Al-Mg-Si alloy and its automotive applications

Al-Mg-Si alloy, also known as 6xxx series aluminium alloy, is one of the heat treatable aluminium alloys and has been an area of research focus for many years (Tisza and Czinege, 2018; Santos et al., 2016). Compared with the other two heat treatable aluminium alloys, i.e. the Aluminium-Copper alloy (Al-Cu, 2xxx series) and Aluminium-Zinc-(Magnesium-Copper) alloy (Al-Zn-Mg-Cu, 7xxx series), the range of the 6xxx series aluminium alloys does not

possess the greatest strength, however they are generally capable of versatile heat treatments for strengthening (Ramesh et al., 2012) and offer good corrosion resistance (Panagopoulos et al., 2009), weldability (Gungor et al., 2014) and moderate formability with medium/high strength (Luan et al., 2016 (a)).

Compared with the non-heat treatable Al-Mg(-Mn) alloy (the 5xxx series), such as AA5182 and AA5754, which have been utilized in aluminium bodied vehicles in the form of cold stamping and warm forming components since the 1990s (Toros et al., 2008), the 6xxx series aluminium alloys show a number of features that are more in line with the requirements of sheet aluminium alloy components in vehicles at present. Firstly, the high strength expands the application of the 6xxx series alloys in vehicles. For example, the yield strength of the component formed from AA6082 after artificial ageing is normally 300 MPa compared with 121 MPa of that formed from AA5754 (El-Fakir, 2015), which enables structural components of the vehicles to be manufactured. Secondly, the 6xxx series alloys exhibit better surface quality after pressing and paint finish compared with the 5xxx series alloys, which are generally prone to develop stain markings due to serrated yielding or strain ageing (European Aluminium Association, 2002 (a)). Therefore, 6xxx series aluminium sheets are also preferred for outer panel applications (Miller et al., 2000). As a result, the usage of 6xxx series aluminium alloy has been gradually increased in recent years. A study by Djukanovic shows that the supply balance between 5xxx series and 6xxx series automotive sheets is tilting towards the 6xxx series progressively and the 6xxx series aluminium alloys have accounted for at least 80% of the current supplied volumes to the automotive manufacturers (Djukanovic, 2019; Scamans, 2017).

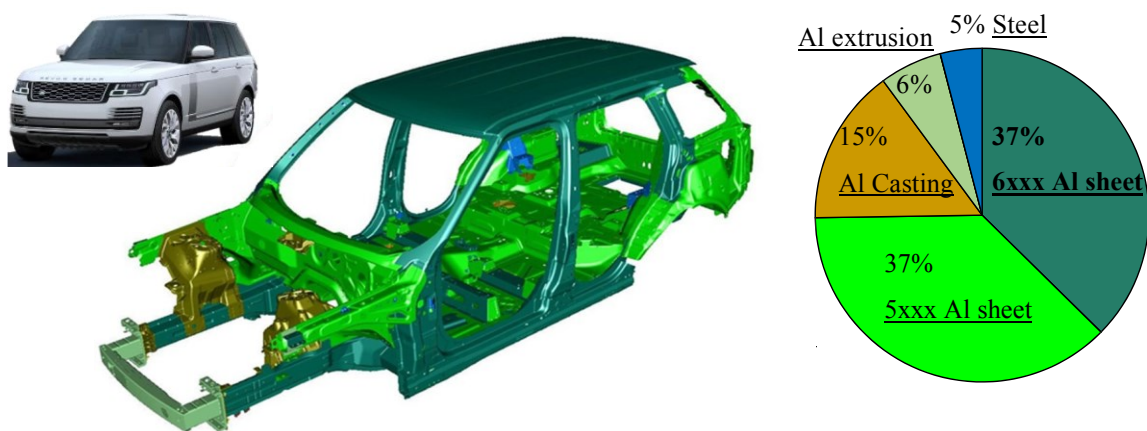


Fig 2.1 Material breakdown of the 2013 Range Rover body-in-white (Black, 2013)

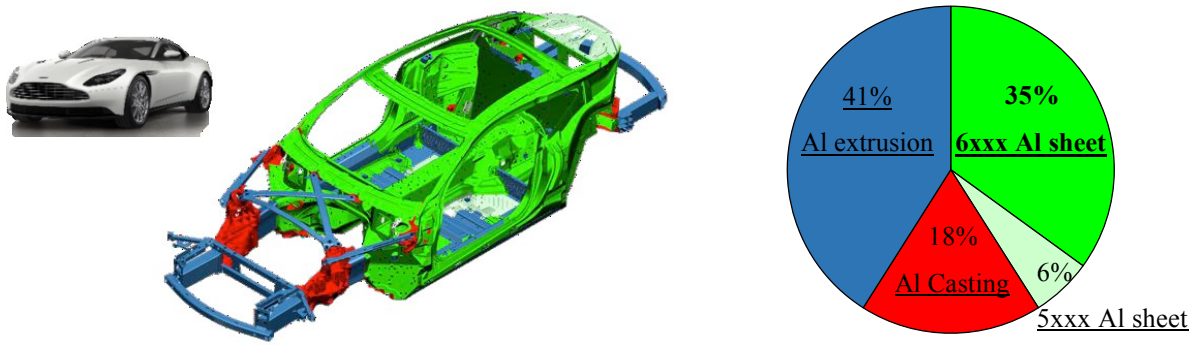


Fig 2.2 Material breakdown of the 2017 Aston Martin DB11 body-in-white (Pugh-Jones, 2017)

The specific grades of the alloys utilized in vehicles are mostly confidential by the automotive manufacturers. In general, the AA6016A and AA6111 are used for the outer and inner body panels and AA6082 is commonly utilized to manufacture the structural components (Bendeyk, 2010). According to the study of two successive generations of Jaguar XJ model, X350 in 2003-2010 and X351 in 2010-present, the percentage of 6xxx series aluminium blank used for the body-in-white witnessed an increase of 72.7% (European Aluminium Association, 2013). The statistics of Range Rover 2013 model and Aston Martin DB11 2017 model also demonstrate that more than one third of the total aluminium body-in-white components have been made of 6xxx series aluminium sheet, as shown in Figure 2.1 and 2.2 respectively (Pugh-Jones, 2017; Black, 2013).

The first commercial Al-Mg-Si alloy *Alloy 51S* was invented and brought to the market in 1921 (ASTM, 1936). In 1930s, another alloy named *Alloy 61S* (AA6061) was developed and capable to meet the requirements on corrosion resistance, weldability and response to heat treatment at that time. A sister alloy *Alloy 62S* (AA6062) with lower chromium content and similar magnesium and silicon content was introduced in 1947, which provided a finer grain size for the product after cold working (Sanders, 2001). The strength of these alloys was as high as 270 MPa and able to take the place of mild steel (370 MPa) in numerous applications. Many other grades of Al-Mg-Si alloys have been developed successively thereafter. As reported by Sato and Matsuda (2003), more than 70 types of Al-Mg-Si alloys have been registered in the Aluminium Association (AA).

The composition limit of some common Al-Mg-Si alloys with contours illustrating the yield stress at the peak aged (T6) condition is demonstrated in Figure 2.3 (Polmear et al., 2017). It can be found that the AA6082 possesses a higher strength compared with other grades of Al-Mg-Si alloys. The ultimate tensile strength (UTS) of AA6082 is normally as high as 340 MPa at the peak aged T6 temper (ThyssenKrupp, 2016). In addition to the sheet metal forming such as the panel components using AA6082, AA6016A and AA6111, the 6xxx series aluminium alloys could also be manufactured by casting and extrusion. For the alloys listed in the Figure 2.3, AA6063 and AA6005 are commonly utilized to make the vehicle chassis components and seat frames by extrusion. AA6061 is used for suspension parts and bumper reinforcements in the form of casting and extrusion (Benedyk, 2010).

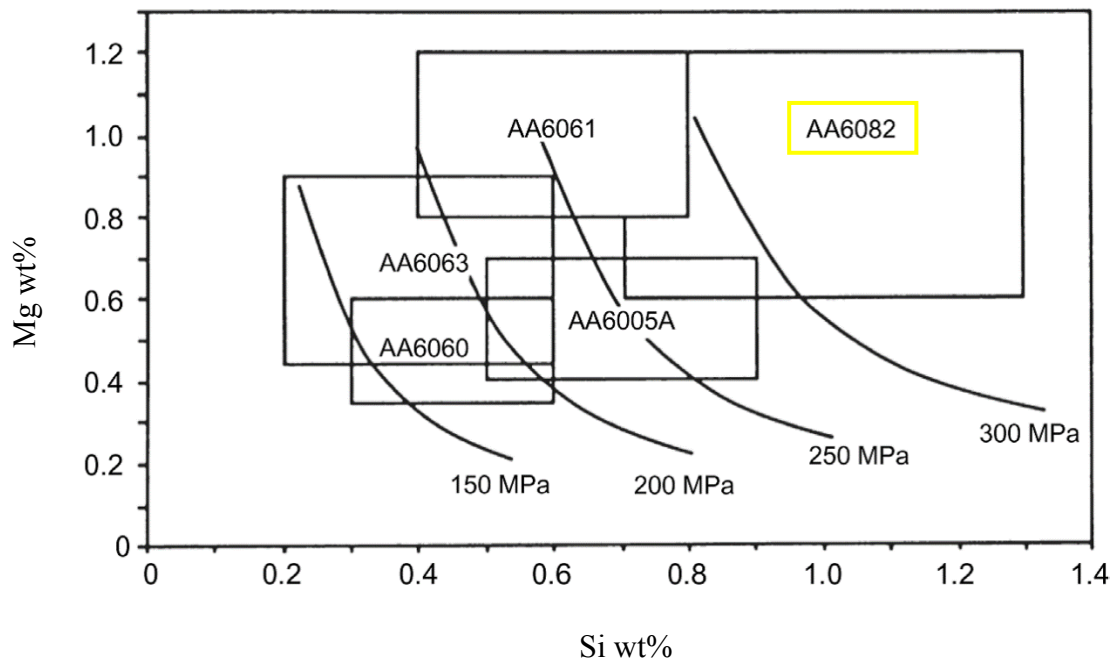


Fig 2.3 The composition limit of some typical Al-Mg-Si alloys, with contours representing the yield strength of these alloys at the peak aged condition (T6) (Polmear et al., 2017)

The production of aluminium sheet generally follows a dedicated thermo-mechanical process, as shown in Figure 2.4 (Engler and Hirsch, 2002). The ingot is first cast and homogenization heat treated followed by a series of hot rolling processes to roll down into blank. As the blank emerges from the tandem mill, it is edge-trimmed and rolled up into a coil. In order to adapt to different applications, further treatment would be conducted such as cold rolling for increasing

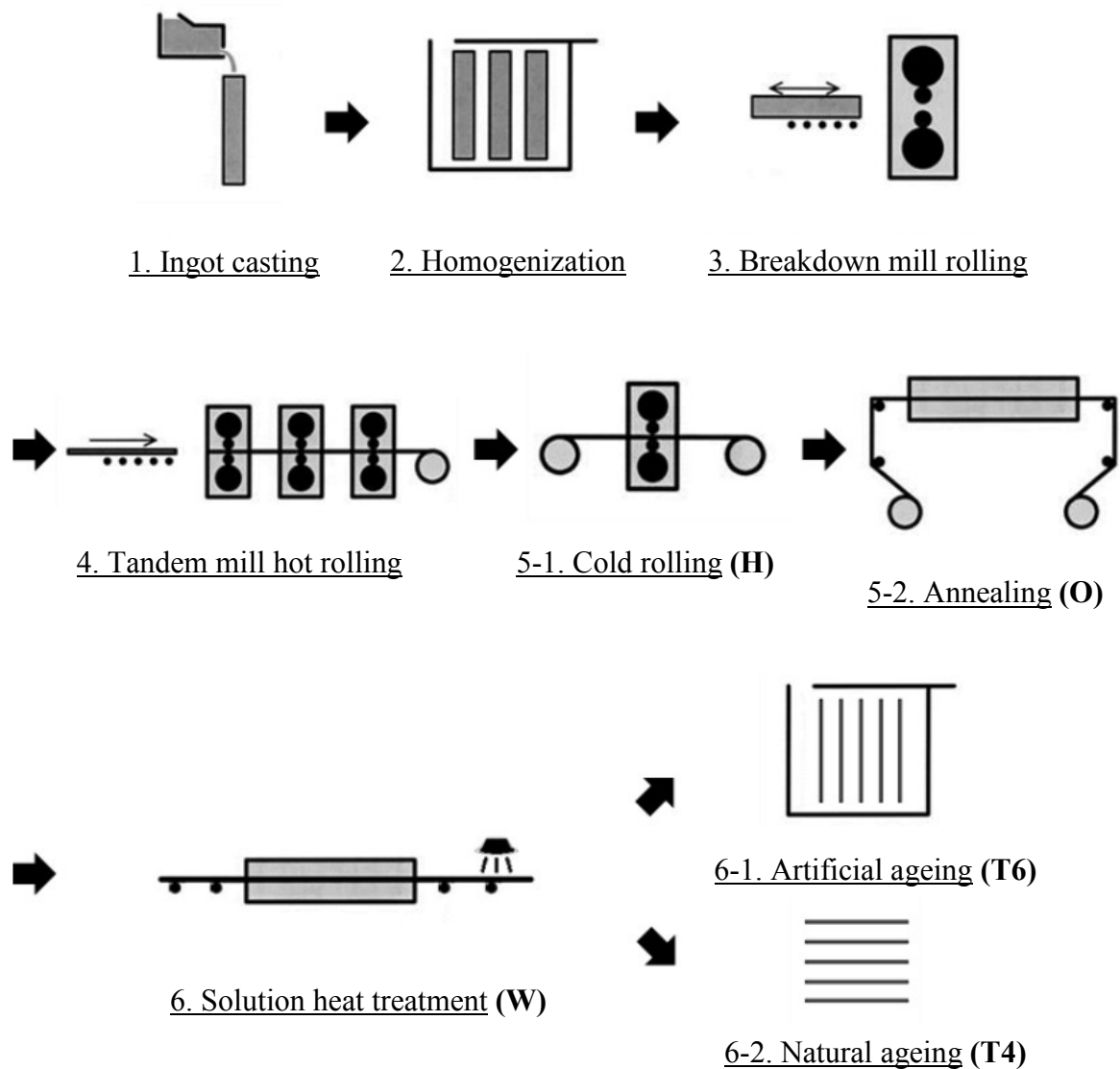


Fig 2.4 Schematic diagram of a typical aluminium sheet production process (Engler and Hirsch, 2002)

strength and thinning, annealing for softening and relieving the internal stress. For the heat treatable aluminium alloys, the sheets would undergo the solution heat treatment, quenching and ageing for precipitation hardening. According to the different ageing temperatures, the ageing could be divided into two categories, natural ageing i.e. room temperature storage for a few days or weeks and artificial ageing i.e. soaking at elevated temperature for 5 to 48 hours (Mrówka-Nowotnik and Sieniawski, 2005). The aluminium sheet is normally endowed with different tempers demonstrating the different thermal and mechanical treatment history during

production, as highlighted in Step 5-1, 5-2, 6, 6-1 and 6-2 of Figure 2.4 respectively. The standard temper designation system for the aluminium alloys can be found in (British Standard, 2017 (a)).

2.2.2 Precipitation hardening of Al-Mg-Si alloy

Precipitation hardening, also known as age hardening, is a strengthening mechanism in many classes of the metal alloys (Gladman, 1999). For the aluminium alloys, it involves three main processes namely the solution heat treatment, quenching and ageing (Miao et al., 1999). In general, a homogeneous solid solution of the alloy was obtained through solution heat treatment. When the alloy is rapidly quenched, an unstable supersaturated solid solution can be produced. The extremely small second-phase particles (normally within 4-8 nm in length and $12nm^2$ in sectional area) are formed and uniformly dispersed in the aluminium matrix during the subsequent ageing process (Pekguleryuz, 2013; Esmaeili et al., 2003 (a)). These particles act as the obstacles to block the movement of the dislocation and thus enhance the strength of the alloys (Martin, 1998). This phenomenon was first noticed by Alfred Wilm in 1908 (Jeffries, 1929), followed by the discovery of other heat treatable aluminium alloys such as AA2025, AA2014 and AA6051 in the 1920s. By 1936, the mainstream of the heat treatable aluminium alloy systems such as Al-Mg-Si (6xxx series), Al-Mg-Cu (2xxx series), Al-Mg-Zn (7xxx series) had been mapped out successively (Hunsicker and Stumpf, 1965).

The current state of the scientific studies suggests that the precipitation hardening process of Al-Mg-Si alloys follows a similar sequence (Yin et al., 2016; Gracio et al., 2004; Esmaeili et al., 2003 (c)) as:

$$\begin{aligned} SSSS \rightarrow \text{clusters} \rightarrow GP \text{ zones (GP I ZONE, including the pre-}\beta'' \text{ phase)} \\ \rightarrow \beta'' \text{ (GP II ZONE)} \rightarrow \beta'/Q' \rightarrow \beta/Q \end{aligned}$$

where the *SSSS* stands for the supersaturated solid solution condition followed by the formation of Si and Mg clusters. *GP zone* is believed to be the spherical clusters with uncertain structure. In some studies (Li et al., 2012), *GP zone* is named as *GP I zone* including the pre- β'' phase and the β'' phase is named as *GP II zone*. The β'' is needle-shaped precipitate with a monoclinic structure. It is regarded as the dominant hardening phase of the Al-Mg-Si alloys

(Du et al., 2012). The composition and lattice parameters of the β'' are still controversial. Some studies showed that the composition of β'' is close to Mg_5Si_6 (Totten et al., 2018). Meanwhile, some studies suggested $Mg_4Al_3Si_4$ is the most likely composition of β'' (Ninive et al., 2014). Depending on the content of Cu in the alloy, the Q' and Q phases would be generated instead of the β' and β phases and the precipitation sequence would change slightly (Li et al., 2012). For example, the aluminium alloy AA6111 is basically the AA6082 with additional copper content for strengthening (Mallick, 2010) and its precipitation sequence follows $\beta'' \rightarrow Q' \rightarrow Q$ (Weatherly et al., 2001). The β' / Q' is lath-shaped precipitate, while some papers consider it as rod-shaped precipitate. As another hardening phase of the Al-Mg-Si alloys, β' provides less strength compared with β'' (Milkereit et al., 2012). The composition of β' is commonly described as Mg_3Si_5 (Cayron and Buffat, 2000). The β phase is plate-shaped precipitate with a composition of Mg_2Si (Vissers et al., 2007). The enrichment of β is generally recognized as the symbol of overageing or annealing of the Al-Mg-Si alloys (Marioara et al., 2006). A comprehensive review of crystal structure and composition of the Al-Mg-Si-(Cu) alloy precipitates was performed by Ravi and Wolverton (2004).

The precipitation hardening process of the Al-Mg-Si alloys is generally characterized through the experimental study and many approaches have been utilized including the hardness test (Ismail and Bouchra, 1992), electrical resistivity measurement (Seyedrezai et al., 2009), differential scanning calorimetry (DSC) (Shen, 2011), positron annihilation spectroscopy (PAS) (Banhart et al., 2012), transmission electron microscopy (TEM) (Yin et al., 2016), high resolution transmission electron microscopy (HRTEM) (Yan et al., 2016) and three-dimension atom probe (3DAP) (Zhong et al., 2017 (a); Zhong et al., 2017 (b)) .

According to (Grau et al., 2016; Li et al., 2015 (a); Esmaili et al., 2003 (b)), the evolution of the yield strength of a solution heat treated and naturally aged AA6111 during the artificial ageing at 180°C is presented in Figure 2.5. It was reported that the optimized artificial ageing temperature of 6xxx series aluminium alloys is around 180°C, and the length of ageing time was between 7 to 10 hours (Wang et al., 2003; Gupta, 2001). In addition, it was found that the natural ageing leads to a prolonged hardening process and degraded ultimate tensile strength (UTS) of the material at the peak aged condition compared with the solution heat treated sample, where 340 MPa vs 325 MPa was observed in the study on AA6111 (Esmaili et al. 2003 (b)).

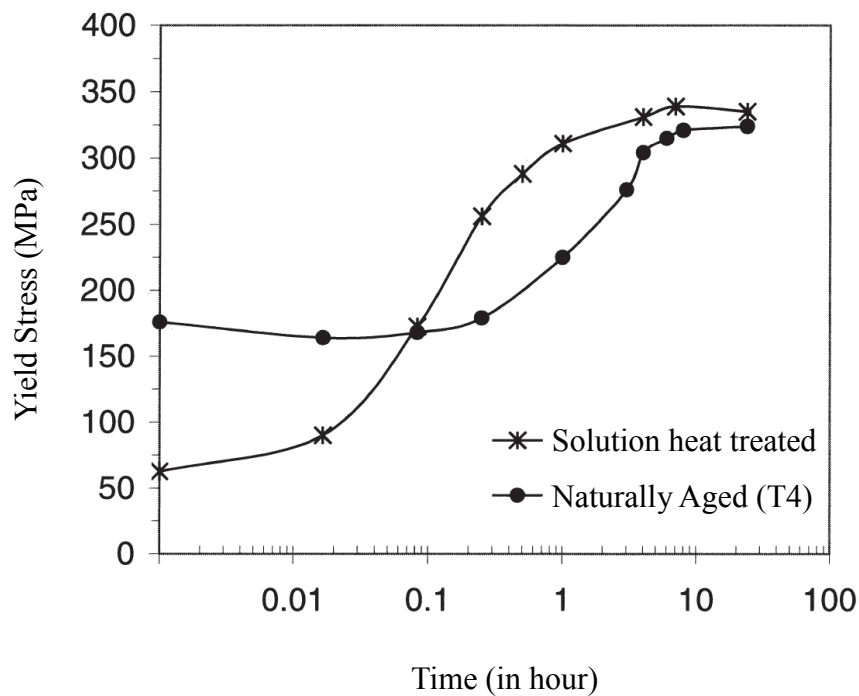


Fig 2.5 The relationship between yield strength and artificial ageing time of the solution heat treated and naturally aged AA6111 during ageing at 180°C (Esmaeili et al., 2003 (c))

Differential scanning calorimetry (DSC) is generally utilized to study the changes of the precipitation states during the precipitation hardening process. It measures the heat absorbed or released by the sample under a continuous heating process at a constant heating rate within 10 K/s (Osten et al., 2015). These endothermic and exothermic reactions correspond to the dissolution and precipitation processes respectively of the material's microstructure and are plotted in the form of the heat flow as a function of temperature in the thermograms (Perkin Elmer Corporation, 2013).

The DSC thermogram of the as-quenched AA6111 sample and samples aged at 180°C for different time is presented in Figure 2.6 (Esmaeili et al., 2003 (c)). A total of five exothermic peaks can be observed in the DSC curve of the as-quenched sample. The results can be interpreted in accordance with the precipitation sequence of the Al-Mg-Si alloys. The exothermic peak associated with the clusters appears only for the as-quenched sample, which implies the formation of clusters has already occurred during the first 5 minutes of the ageing process before the measurement. For the most distinct exothermic peak associated with β'' for

the as-quenched sample, the heat flow decreases and eventually becomes an endothermic trough, marked as *A* in Figure 2.6, for the samples with increased ageing time from 15 minutes to 7 hours. This reflects the fact that more β'' are generated during the artificial ageing so more dissolution reactions and endothermic heat are observed during the DSC test, especially for the samples at the peak aged condition which is aged at 180°C for 7 hours. Similar thermograms can be found for other types of 6xxx series aluminium alloys, such as AA6022 (Shen, 2011), AA6016 (Birol and Karlik, 2006; Birol, 2005 (a)) and AA6005A (Milkereit et al., 2014).

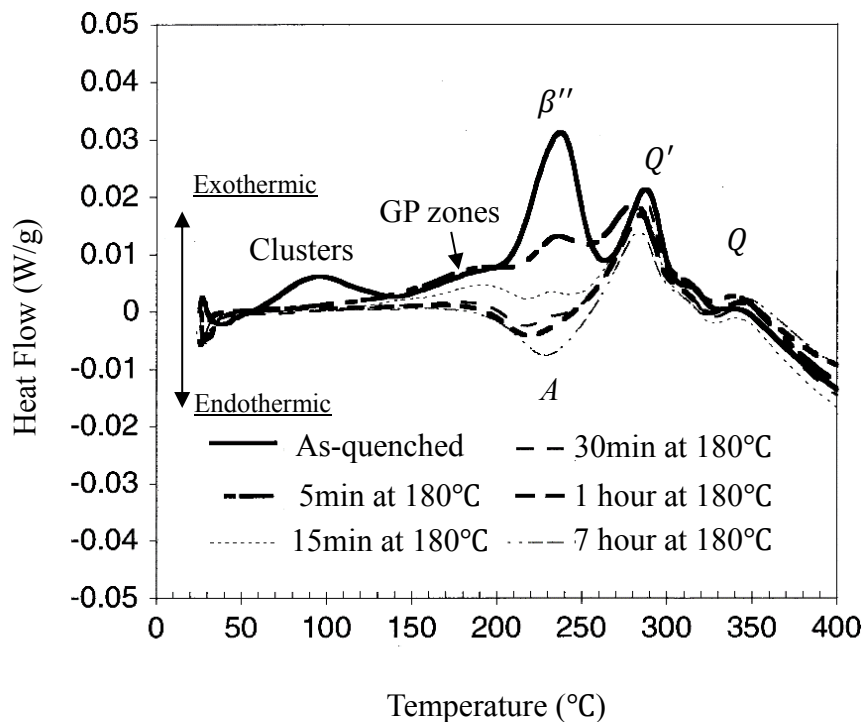


Fig 2.6 The DSC thermograms of the AA6111 samples at as-quenched condition and with various ageing time at 180°C (Esmaeili et al., 2003 (c))

Figure 2.7 (a) shows the microstructure of aluminium alloy AA6111 at the peak aged condition, i.e. solution heat treated, water quenched and soaked at 180°C for 7 hours (Wang et al., 2003). Two types of precipitates can be identified according to their geometries and the diffraction patterns of the selected area. One is β'' with needle shape and circular in the cross section. The strain field contrast is clearly visible around these precipitates, which implies the coherence of precipitates and the aluminium matrix. The other is identified as Q' by the lath shape and rectangular cross section with larger size. In addition, the extra reflections can be found in the

diffraction pattern of the β' as shown in Figure 2.7 (b) and (c), demonstrating the difference on the geometry between β'' and β' .

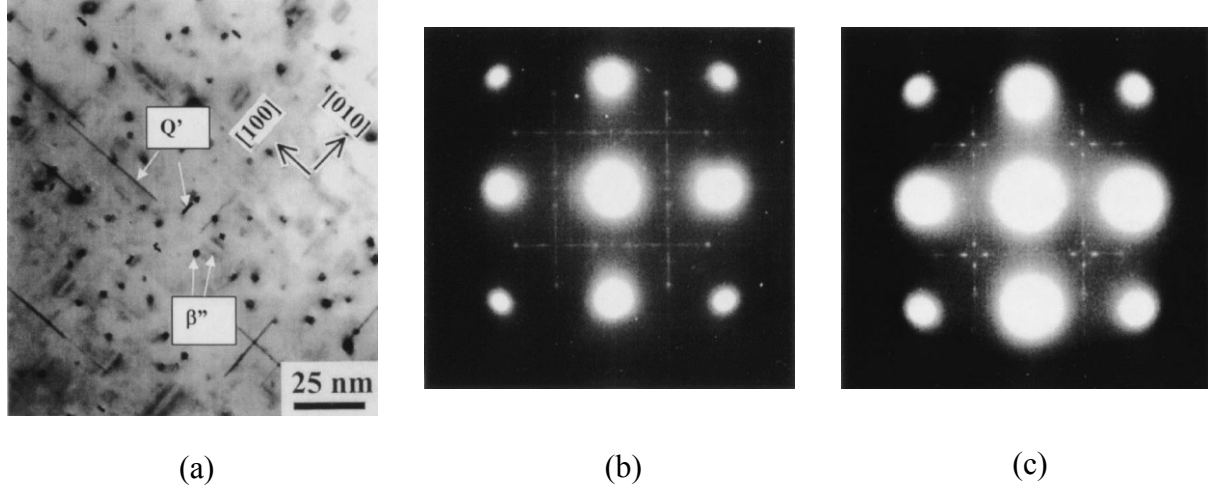


Fig 2.7 (a) TEM graph of Al-Mg-Si alloy at the peak aged condition (7 hour at 180°C) along $\langle 001 \rangle$ direction, (b) Selected area diffraction pattern referring to the needle-shaped precipitates β'' and (c) Selected area diffraction pattern referring to the lath-shaped precipitates Q' (Wang et al., 2003)

Through the morphology analysis of the microstructure using TEM, the typical appearances of different precipitates can be used to identify the specific type of precipitation particle as well as the precipitation condition of the material. A series of TEM scans for the aluminium alloy AA6111 solution heat treated and artificially aged at 180°C with different time are summarized in Figure 2.8 (Ninive et al., 2014; Fallah et al., 2014; Teichmann et al., 2012; Wang et al., 2003). For the Figure 2.8 (a) - (d), it can be observed that volume fraction of the precipitates are increasing progressively during the ageing process until the peak aged condition. Both β'' and β' can be identified by their appearances. The results are consistent with the increased yield strength of the material and the increment of the endothermic trough of the samples with various ageing levels at 180°C in the DSC thermograms. For the over-aged condition, Figure 2.8 (e), the needle shaped particles are replaced by the plate-shaped particles with larger dimension and lower volume fraction. Such particles can be defined as the Q phase and are responsible for the degraded strength (Teichmann et al., 2013).

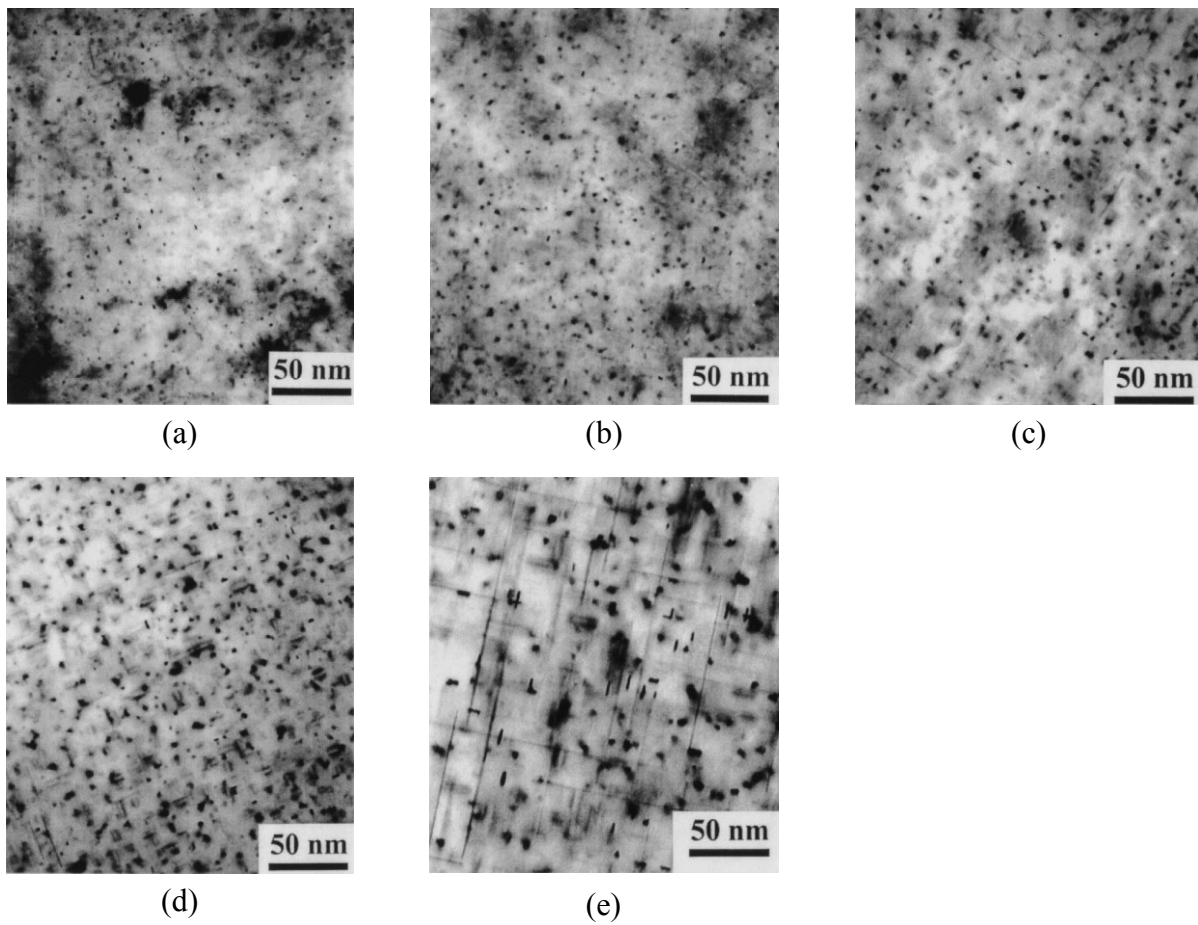


Fig 2.8 TEM graphs of AA6111 sample aged at different conditions (a) 180°C/15 min, (b) 180°C/30 min, (c) 180°C/1 hour, (d) 180°C/7 hours, (e) 180°C/24 hours (Wang et al., 2003)

As one of the most complex alloy systems, there still remain some gaps in understanding the effects of the processing parameters on the precipitation hardening behaviour of Al-Mg-Si alloys and this has drawn the attention of significant research work (Ernst, 2004). The precipitation hardening behaviour highly depends on the artificial ageing time and temperature, which control the type, the volume fraction and size distribution of the precipitation particles and therefore the strength of the material during the forming and ageing processes (Ozturk et al., 2010). Many studies, such as multiple stage ageing (Abdulwahab et al, 2011), pre-ageing (Engler et al., 2015) and pre-straining (Kolar et al., 2012) have been conducted to obtain the desired types of hardening phase and increase the volume fraction of these particles in order to achieve the optimized strength of the alloy in a short time. Given longer ageing time and higher ageing temperature, normally over 10 hours and 250°C, the precipitates corresponding to the

peak aged condition would be altered by more stable precipitates. Therefore, some research revolves around the overageing and annealing phenomena of the Al-Mg-Si alloys (Li et al., 2015 (a)). In addition, the interaction of natural ageing and the subsequent artificial ageing of the 6xxx series aluminium alloys is also studied by some researchers (Cuniberti et al., 2010; Marioara et al., 2003). It has been found that the natural ageing has a degraded effect on the subsequent artificial ageing response of the aluminium alloy AW-6082. Compared with the samples without natural ageing, longer β'' precipitates with lower number density and volume fraction were observed for the samples with 7 days of natural ageing at the peak aged condition (Cuniberti et al., 2010). Moreover, the main hardening phases such as β'' and β' can be generated only after the dissolution of these clusters during the artificial ageing. A portion of the solute atoms Mg and Si have been consumed during this process and thus leads to a degradation on the strength of the material after the artificial ageing (Birol, 2005 (b); Mrówka-nowotnik and Sieniawski, 2005).

2.2.3 Modelling the precipitation hardening process

In addition to the experimental study, the modelling and quantification of the precipitation hardening process have been performed in the literature (Myhr et al., 2010; Guo and Sha, 2002). The modelling work of the precipitation hardening process were mostly based on the “Friedel effect” (Friedel, 1964) and Orowan’s theory (Orowan, 1948), as explained in Figure 2.9. In these theories, the precipitation particles are regarded as an array of unified sphere shaped obstacles. When the gliding dislocation line is blocked by these particles, it bows out. If the precipitation particles are small and with low strength, they would be shorn by the moving dislocation line with the increasing stress. The strength of the material comes from the resistance to shear of these particles. The critical stress enquired to make dislocations move through the array of precipitates is referred as critical resolved shear stress (CRSS). It initially increases with the particle radius, as shown in Figure 2.10. As the precipitation particles grow in size during the ageing, it becomes difficult for the dislocation line to cut through them. The Orowan mechanism would dominate the process thereafter. The two positive segments and one negative segment of the dislocation would annihilate one another, generating a new dislocation bypassing the particle and leaving a loop around the particle. As a result, it becomes easier for the dislocation to bypass the particles (Osuch et al., 2018).

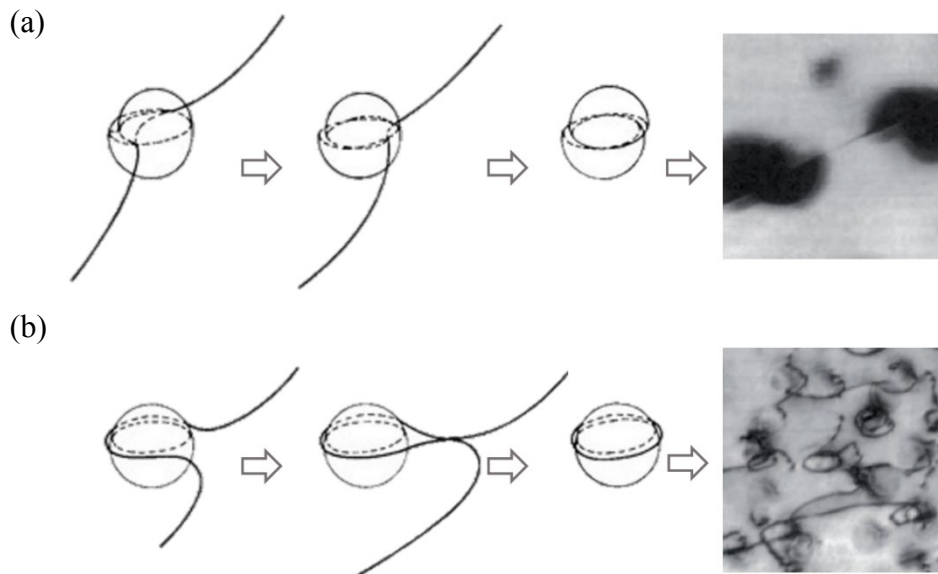


Fig 2.9 Precipitation hardening mechanisms: moving dislocations pass small precipitates by (a) shearing, whereas large and hard particles are generally bypassed by (b) bowing (Martin, 1998)

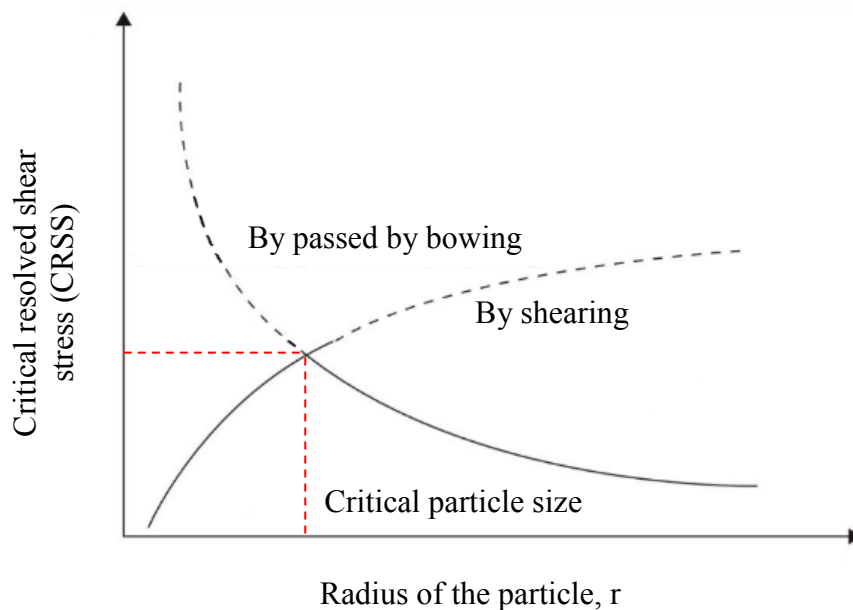


Fig 2.10 Schematic diagram of the critical resolved shear stress (CRSS) versus the size of precipitation particles by shearing or bypassed by bowing (Martin, 1998)

One of the classical precipitation hardening models utilizing these theories was proposed by Shercliff and Ashby (1990 (a)). The model was an overall process model describing the

evolution of the yield strength throughout the artificial ageing process. In this model, the material internal state variables, such as solute concentration in the matrix, volume fraction of precipitates and mean particle radius were correlated to the yield strength. The strength of the alloy is regarded as a combination of the intrinsic strength of the aluminium matrix, the solid solution strength which decreases as precipitation proceeds and the combined effects of particles shearing and bypassing, as shown in Figure 2.11.

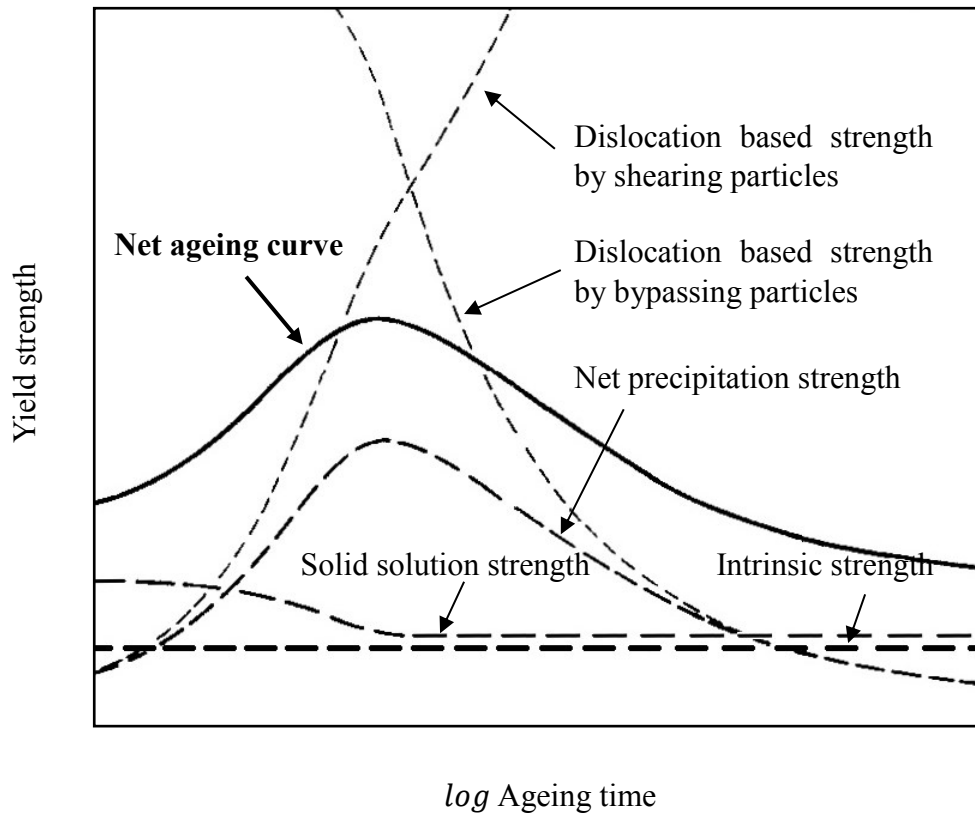


Fig 2.11 Schematic diagram of the individual contributions to the yield strength of the material (Martin, 1998)

The yield stress of the material $\sigma(t)$ during the ageing process is expressed as:

$$\sigma(t) = \sigma_i + \Delta\sigma_{ss} + \Delta\sigma_{ppt} \quad (\text{Equ. 2.1})$$

where σ_i is the intrinsic strength of pure aluminium, $\Delta\sigma_{ss}$ is solid solution strength and $\Delta\sigma_{ppt}$ is the contribution of precipitation hardening.

The strength induced by the precipitation particles is further expressed by the harmonic mean of the contributions of precipitate shearing and bypassing as:

$$\Delta\sigma_{ppt} = \left[\frac{1}{\Delta\sigma_{shearing}} + \frac{1}{\Delta\sigma_{bypassing}} \right]^{-1} \quad (\text{Equ. 2.2})$$

The model has been proved capable of predicting the precipitation hardening behaviours of AA6082 and AA6016 under different ageing time and temperatures. Moreover, it was applied to predict the strength loss of the heat-affected zones of welds due to parabolic thermal cycles (Shercliff and Ashby, 1990 (b)).

Many studies have been built on Shercliff and Ashby's work and refine the model in a more capable and accurate manner. Holmedal et al. studied the effect of non-spherical particles such as needle or plate shaped precipitation particles in Al-Mg-Si alloys during the artificial ageing heat treatment. Correction factors were proposed accounting for the influence induced by the particles' shape on the growth kinetics (Holmedal et al., 2016). Esmaeili et al. modelled the precipitation hardening behaviour of the pre-aged Al-Mg-Si-(Cu) alloy. The volume fraction of precipitates during the artificial ageing is expressed as a sum of two parts. One is the volume fraction of precipitates in the as-pre-aged material and the other is the portion due to the artificial aging process (Esmaeili and Lloyd, 2005). The combined effects of room temperature storage and cold deformation on the AA6082 and AA6063 were taken into account in the model proposed by Myhr et al. (2015). Furthermore, in addition to simulating the iso-thermal age hardening process, the model developed by Sepehrband et al. is able to describe the microstructural evolution of the aluminium alloy AA6451 during the non-isothermal annealing process. The interactions of recovery, recrystallization and precipitations are considered in the model (Sepehrband et al., 2015).

2.3 Forming technologies for manufacturing sheet aluminium alloy components

Cold stamping is the most widely used forming technology for manufacturing sheet aluminium alloy components at present and warm forming has been employed by a few vehicle manufacturers in recent years (Zheng et al., 2018 (a); Mori et al., 2009). However, the formability of the aluminium sheets is still limited through these processes, especially for complex shapes of some automotive panel components (Altan and Ju, 2015; Kaufman, 2008).

In light of this, several sheet metal forming technologies, such as solution heat treatment, forming and cold-die quenching (HFQ), superplastic forming (SPF) of aluminium alloys and W-Temper forming have been developed.

2.3.1 Solution heat treatment, forming and cold-die quenching (HFQ)

The Solution Heat Treatment, Forming and In-Die Quenching (HFQ) is a hybrid hot forming process, which takes advantage of elevated forming temperature, combines the forming and quenching in one process and attains high post-form strength through the subsequent artificial ageing (Lin et al., 2008).

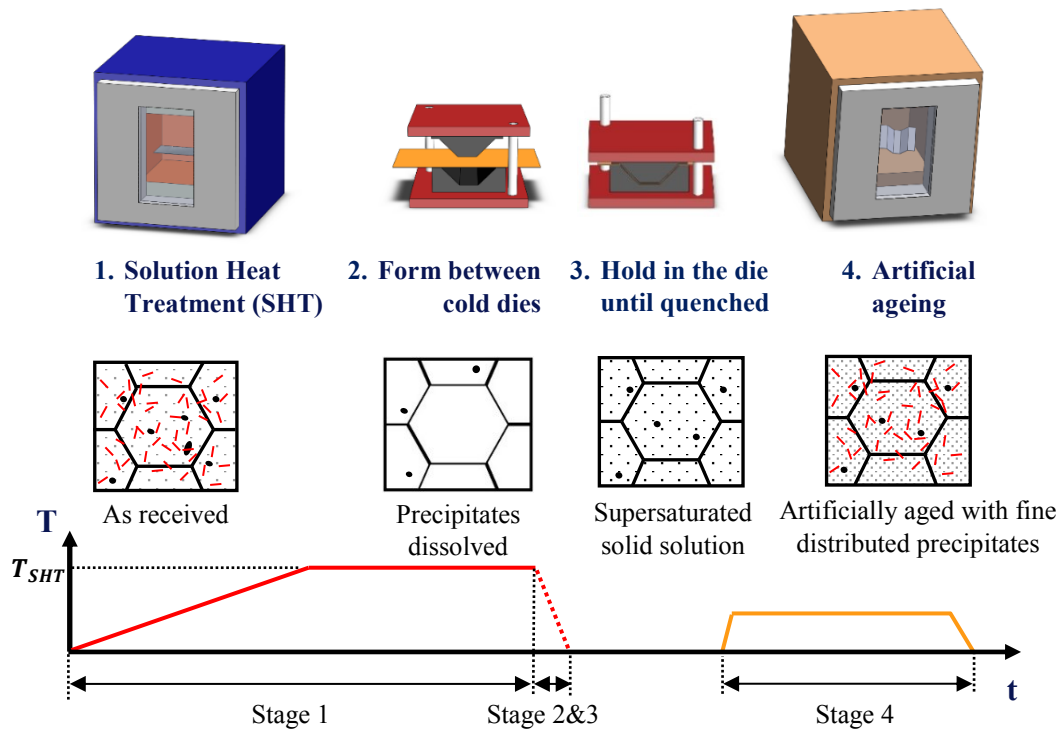


Fig 2.12 Schematic diagram of the HFQ process

In this process, the aluminium blank is first heated to its solutionizing temperature and soaked for a specified period of time in the furnace to conduct the solution heat treatment (SHT). The SHT temperature for 6xxx series aluminium alloy is approximately 525°C, and the soaking time is normally five minutes in the HFQ process (Isadare et al., 2013; Mohamed et al., 2012). Since the alloying elements and precipitates mostly dissolve into the aluminium matrix during the SHT, there are few obstacles to the movement of the dislocation. The yield stress is largely

reduced, and the material becomes increasingly formable, enabling a more complex shape to be formed. The hot blank is then transferred to the cold forming tools rapidly, stamped and quenched to the ambient temperature. The forming and in-die quenching maintain the supersaturated solid solution (SSSS) within the aluminium matrix and promote the precipitation hardening of the formed component during the subsequent artificial ageing. The temperature profile and microstructure evolution of the material during the HFQ process is schematically presented in Figure 2.12.

Studies have revealed that several types of non-heat treatable and heat treatable aluminium alloys can be applied in the HFQ process. For example, El Fakir (2014) studied the influence of forming parameters of the HFQ process on the thickness distribution of the formed part using AA5754. A feasibility study of HFQ using AA2060 was conducted by Gao et al. (2016). The application of HFQ for the AA6082 tailor welded blank was explored by Liu et al. (2016). Fan studied the dependence of hardness on solution heat treatment time of AA6A02 under the HFQ process (Fan et al., 2013).



Fig 2.13 HFQ formed door inner of LOTUS concept car (Politis et al., 2013)

The HFQ process has been gaining increasing interest from the automotive industry in recent years. In 2015, a door inner component was produced for a LOTUS concept car, as shown in Figure 2.13. The geometry of this component is 1500 mm x 830 mm x 200 mm with sharp corners and complex central features. After sufficient artificial ageing treatment, the overall hardness was over 110 Hv which is 94% of the as delivered T6 temper blank (Politis et al., 2013). The HFQ process has also been applied by Aston Martin and Morgan Motors to

manufacture the A-pillar component (Pugh-Jones, 2017) and cross member component of the chassis (TWI, 2018), as presented in Figure 2.14 and Figure 2.15 respectively.



Fig 2.14 HFQ formed A-pillar of Aston Martin DB11 (Pugh-Jones, 2017)



Fig 2.15 HFQ formed cross member of Morgan Aero 8 sports car (TWI, 2018)

The HFQ process is considered as an attractive forming technology to expand the application of aluminium panel components due to the improved formability of the aluminium sheets. It enables large components with high complexity to be formed in one action rather than welding and joining of small stamped parts. According to the literature (Liu et al., 2016; El-Fakir et al., 2014), the true fracture strain of AA5754 and AA6082 are over 1.4 at 520°C and 0.7 at 535°C respectively under a strain rate of 1/s. In addition, it has been reported that the HFQ formed cross member components, as shown in Figure 2.15, reduce the number of assembly parts from 11 pieces to 8 pieces and a mass reduction of 32% or 2.36 kg (Impression Technologies, 2018). Components formed by the HFQ process are also characterized by high geometric accuracy, since the sheet metal is formed at high temperature and directly quenched to the ambient temperature, which restrains the springback and geometry distortion. Moreover, the high post-form strength can be achieved for the heat-treatable aluminium alloys through the subsequent artificial ageing. The hardness of a HFQ formed and aged AA7075 floor panel component was found to be 170 Hv, which is over 92% of the original material in T6 temper (Zhang et al., 2016; Herrman Pratulon et al., 2014).

To form the complex shaped component with a high post-form strength, the HFQ process requires a long cycle time. According to Cox (2019), the solution heat treatment of the blank

generally takes 900 seconds and the post-form artificial ageing is up to 8 hours. Furthermore, it was found that the ductility of some aluminium alloys, such as AA2024, decreased significantly at the solutionizing temperature due to the low strength grain boundaries and intergranular fracture (Wang et al., 2011). The forming process therefore needs to be conducted in two steps (Gao et al., 2016). In the two-step process, the blank is first heated to the target temperature for maximum ductility followed by stamping using heated dies. The formed piece is then solution heat treated in a separate furnace and quenched between the cold dies with identical geometry to the ambient temperature (Lin et al., 2018).

2.3.2 Superplastic forming (SPF) of aluminium alloys

Superplastic forming is a manufacturing process, which makes use of the superplasticity of some types of metal alloys and realizes an elongation to failure of 300% to over 1000% under the specific forming conditions of temperature and strain rate (Giuliano, 2012). In general, the strain rate is lower than $10^{-3}/s$ and the forming temperature is greater than $0.5T_m$ (T_m is the melting point) (Rowe, 2012). Given the superior formability, SPF is commonly used for forming thin-wall components with large dimensions and extremely high plastic strain level into the near-net shape (Mouritz, 2012).

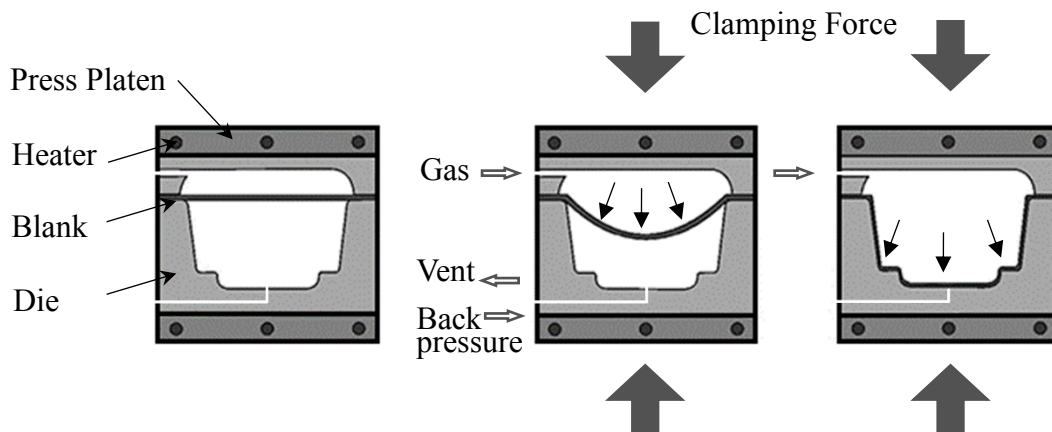


Fig 2.16 Schematic diagram of the gas blowing SPF process (Mechanica Technical Solutions, 2019)

SPF of aluminium sheet is mainly conducted in the form of gas blow forming (Langdon, 2009). As an isothermal forming process, the forming tools are either entirely placed within a furnace

or assembled with heating platens containing cartridge heaters (Bernart, 2011). The successive steps of the forming process are schematically presented in Figure 2.16 (Mechanica Technical Solutions, 2019). The aluminium blank is clamped in between the press platen and the die and heated to the dedicated forming temperature. Pressure, typically between 10 to 30 bar, is applied over the blank through gas injection. Either air or inert gas, e.g. argon gas, can be utilized (Degarmo et al., 2003). The sheet is then stretched into the die under the forming pressure. The lower cavity can be held under vacuum conditions or with back pressure to realize precise control and suppress the cavitation, which leads to the degradation of strength and corrosion (Pilling and Ridley, 1986). The forming process proceeds at the high forming temperature until the deformed sheet alloy firmly contacts the die.

The SPF requires the material being processed in advance to develop the uniform and equiaxed microstructure, which could also remain stable during the superplastic deformation. The grain size of the material is typically less than 10-20 μm (Ridley, 2011). For example, 6.89 μm of SP8090 observed by Wu (2000) and 8.32 μm of SP5083 measured by Chentouf et al. (2017). Table 2.1 summarizes some SPF aluminium alloys of commercial interest with their superplastic properties.

Table 2.1 The composition, SPF temperature, strain rate and elongation of some superplastic aluminium alloys (Ridley, 2011; Smolej et al., 2001; Troeger and Starke, 2000)

Type	Composition wt%	SPF temperature	Strain rate	Elongation%
AA2004	Al-6Cu-0.4Zr	460 °C	$\sim 10^{-3}/\text{s}$	800-1200
AA2090	Al-2.5Cu-2.3Li-0.12Zr	530 °C	$\sim 10^{-3}/\text{s}$	~ 500
AA5083	Al-4.5Mg-0.7Mn-0.1Zr	500-520 °C	$\sim 10^{-3}/\text{s}$	~ 300
AA6013	Al-0.8Mg-0.7Si-0.8Cu-0.3Mn-0.1Fe	520 °C	$3 \times 10^{-4}/\text{s}$	~ 230
AA7475	Al-5.7Zn-2.3Mg-1.5Cu-0.2Cr	515 °C	$2 \times 10^{-4}/\text{s}$	800
AA8090	Al-2.4Li-1.2Cu-0.7Mg-0.1Zr	530 °C	$5 \times 10^{-4}/\text{s}$	1000

So far, the superplastic forming process of aluminium alloys has been employed in more than forty models of aircraft and twenty different models of vehicles (Kappes et al., 2010). For example, the front fender of Morgan AeroMax was formed by SPF in 2010, as shown in Figure 2.17 (Grimes, 2011). The length of this component is more than 2 meters. Bentley has applied this technology to craft a more complex-shaped body side panel for the new model Continental

GT in 2018, realizing an 85 kg weigh reduction over the component in steel, as shown in Figure 2.18 (Rösner-Kuhn, 2018).



Fig 2.17 Superplastic formed front fender (left) of Morgan AeroMax (right) (Grimes, 2011)



Fig 2.18 Superplastic formed body side panel (left) of BENTLEY Continental GT (right) (Rösner-Kuhn, 2018)

In addition to the exceptional formability achieved, the SPF is characterized by the outstanding dimensional accuracy and surface finish of the formed components with the springback and residual stress being eliminated (Barnes, 2007). Large components with complex features can be made as a single piece, reducing the assemblies and weight, which is favourable for automotive applications. The post-form strength is well maintained for the non-heat treatable aluminium alloys and can be improved by artificial ageing for the heat treatable aluminium alloys. According to the study by Chen et al. (2004), the post-form tensile strength of 5083 SPF is approximately 300 MPa on UTS and 150 MPa on yield stress, compared with 305 MPa and 160 MPa respectively for the as-delivered material. For the 7475 SPF, the strength of the as-formed components was improved from 400 MPa to 550 MPa on UTS and from 250 MPa to 460 MPa on yield stress after sufficient artificial ageing. Moreover, SPF benefits from the reduced tooling cost, as only a female or male die is required (Kridli et al., 2010).

However, SPF is a time-consuming forming process, which can take 0.5 hours or greater to produce one component. The lengthy cycle time restricts its application to low volume production only (Liu et al., 2011). Some modified SPF processes have therefore been developed to improve the production efficiency. Luo utilized the mechanical pre-forming followed by SPF and reduced the cycle time to 3 minutes (Luo et al., 2008). Quick Plastic Forming (QPF) patented by General Motors was able to keep the cycle time within 5 minutes through a much faster deformation rate (Powell, 2012). As the superplastic behaviour of the material only occurs at a narrow range of forming temperature and strain rate, precise control on the changing forming pressure throughout the forming process is required (Chen et al., 2004). Furthermore, the aluminium alloys for the SPF process are generally specially produced to obtain superplasticity, which involves extra solution heat treatment, over ageing, cold working and recrystallization in addition to the normal aluminium blank production route and leads to high material costs (Smolej et al., 2001).

2.3.3 W-Temper forming

In addition to forming the aluminium sheets at elevated temperatures, prior heat treatment followed by forming at ambient temperature has been reported as a possible approach to improve the formability of the aluminium alloys (Li et al., 2015 (b)). W-Temper forming is such a process, which lowers the strength of the heat treatable aluminium alloys temporarily through solution heat treatment and rapid quenching and increases the ductility of the material during the deformation (Sáenz de Argandoña et al., 2015).

The W-Temper forming process is comprised of four main stages; the temperature history and the microstructure evolution of different stages are shown in Figure 2.19. In the first stage, the blank is heated to the SHT temperature and maintained in the furnace for the solution heat treatment. Secondly, the hot blank is transferred to a water bath using a robot arm and rapidly quenched to room temperature in order to achieve the supersaturated solid solution (SSSS) microstructure. It is essential that the blank is then formed rapidly, e.g. <10 seconds, to avoid the effects of natural ageing which increases the strength of the aluminium sheet during the forming process. After forming, the component could be artificially aged to improve the post-form strength (Mendiguren et al., 2016).

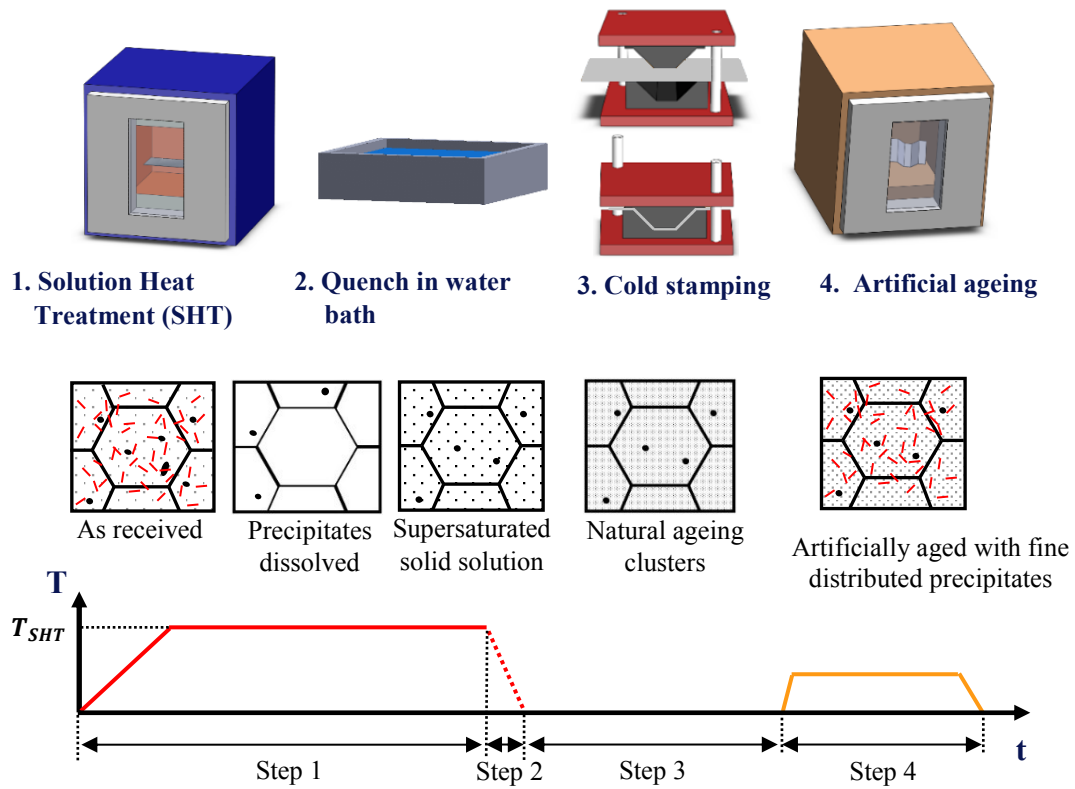


Fig 2.19 Schematic diagram of the W-Temper forming process

The research of W-Temper forming mainly revolves around 7xxx series aluminium alloys at present, considering the high strength compared to other series of aluminium alloys. Two components utilized in vehicles have been formed in laboratory scale successfully, as shown in Figure 2.20. One is a B-pillar panel of a passenger vehicle (Sáenz de Argandoña et al., 2015) and the other is a front side member in the chassis of the Volkswagen Touran (Mendiguren et al., 2016).

As a cold forming process in essence, W-Temper forming largely simplifies the forming process and shortens the manufacturing cycle time. The forming tools of cold stamping can be directly used (Hoffmann et al., 2007). According to (Mendiguren et al., 2016), the blank for the front side member was heated to 480°C in 300 seconds and soaked for another 300 seconds. The transfer time takes approximately 7 seconds and no in-die quenching stage is required. In addition, the W-Temper forming process offers a moderate improvement on the material's ductility. For aluminium alloy AW-7921, the UTS decreases from 590 MPa to 350 MPa and the true fracture strain was increased from 0.1 to 0.25 compared with the material in the T6

temper at room temperature (Kumar and Ross, 2016). Schuster et al. (2019) showed that the true fracture strain of AA7075-W is 0.26 at room temperature, which is close to the value of 0.29 for the material under warm forming condition at 320°C.



Fig 2.20 W-Temper formed vehicle B-pillar (left) (Sáenz de Argandoña et al., 2015) and Front side member of Volkswagen Touran (right) (Mendiguren et al., 2016)

However, the W-temper is reported to be a highly unstable condition of the material. Due to a large number of the quench-in vacancies, the solute atoms can rapidly diffuse and gather into clusters and GP zone, leading to a rapid increase in the material strength during the storage (Zheng, et al., 2018 (b)). Cao et al. found that the hardness of an Al-Mg-Si-Cu alloy after solution heat treatment increased by 37% from 44 Hv to 60 Hv during 3 hours room temperature storage (Cao et al., 2013). For the Al-0.48Mg-1.07Si-0.29Cu alloy, the yield strength increased from 50 MPa to approximately 100 MPa in 3.5 hours (Rometsch et al., 2011). As a result, the time window between solution heat treatment and stamping is narrow. Mohammadi et al. claimed that the W-tempered sheets should be formed no longer than 1 hour after SHT (Mohammadi et al., 2013). The post-form strength can be enhanced after the subsequent artificial ageing, while, the response to artificial ageing is not as pronounced as the hot stamping process due to the existence of the natural ageing clusters. Cao et al. reported that one hour storage at room temperature after solution heat treatment for an Al-Mg-Si-Cu alloy resulted in 25 Hv reduction on the artificial ageing response when aged at 170°C for 30 minutes (Cao et al., 2013). Moreover, the W-Temper forming is subject to higher strain level and strain hardening effects during the deformation than the hot stamping process, which leads to more springback of the formed components. According to the 3D scanning of the front side member components, shown in Figure 2.20, formed by hot stamping and W-Temper process

respectively, it was found that the hot stamping maintained the deviation on geometry of the sidewall and flange within 1.5 mm, while the corresponding areas of the W-Temper formed component exceeded 3 mm (Mendiguren et al., 2016).

2.4 Summary

In this chapter, the mechanical properties and application of Aluminium-Magnesium-Silicon (Al-Mg-Si; 6xxx series) alloys have been reviewed. Due to the age hardening characteristics, medium/high strength and the moderate formability, 6xxx series aluminium alloys have been widely utilized to manufacture light weight panel components especially in the automotive industry. The precipitation hardening mechanism of the Al-Mg-Si alloys including the precipitation sequence, properties of the precipitation particles are demonstrated. The typical TEM graphs of the precipitation particles at different artificial ageing conditions are summarized. β'' with needle shape and a circular cross section is regarded as the dominant hardening phase of the alloy and its volume fraction increases with the artificial ageing process before the peak aged condition. The classical theories, Friedel effect and Orowan theory, describing the precipitation hardening process are also presented.

Three sheet metal forming technologies for aluminium alloys including the solution heat treatment, forming and cold-die quenching (HFQ), superplastic forming (SPF) of aluminium alloys and W-Temper forming are reviewed covering the main forming stages, improvements and limitations. These forming technologies have the main advantage of improved formability. However, the solution heat treatment, low deformation rate of SPF and artificial ageing process for strengthening lead to a prolonged manufacturing cycle time from 3 minutes to over half an hour, which may limit these forming technologies to only the low and medium production volumes.

Through the literature review, it was found that the research of sheet metal forming technologies generally revolves around the effects of forming temperature and forming speed. Studies on the influence of heating rate, especially the ultra-fast heating rate on the heat treatable aluminium alloys, are still insufficient. Meanwhile, the forming temperature of these studies are usually below a certain level i.e. 250°C for processes such as cold stamping and warm forming, or as high as the SHT i.e. 535°C for 6xxx series aluminium alloys for different types of hot stamping processes. There is a lack of research specifically centring on the forming temperature between

300°C and 500°C. Moreover, the 6xxx series aluminium blanks are typically produced as different tempers, such as the T4 and T6 tempers. The effects of the material temper during the ultra-fast heating processes are also not yet clear. In addition, the dedicated test facilities that enable the ultra-fast heating of aluminium blanks have yet to be developed.

Significant progress has been made in the development and application of sheet metal forming technologies for aluminium alloys in recent years. While more components have been successfully formed and utilized in vehicles, novel forming technologies which can take account of formability, post-form strength, manufacturing cycle time, energy consumption and equipment & material cost at the same time are desirable to further extend the applications of aluminium panels in the automotive industry.

Chapter 3

Fast light Alloy Stamping Technology (FAST) and the dedicated pilot production line Uni-Form

3.1 Introduction

In this chapter, a novel Fast light Alloy Stamping Technology (FAST) distinguished by an ultra-fast heating stage is proposed. FAST is aimed at enabling the mass production of complex-shaped aluminium panel components particularly in the automotive industry with high post-form strength, short cycle time, minimal energy consumption and equipment required. The concept and feasibility of the FAST process are explained in this chapter and the process specifications are illustrated. In addition, a pilot production line Uni-Form dedicated for the FAST process is developed. Uni-Form is able to realize the ultra-fast heating through contact heating, achieve the precision processing parameters control and conduct the forming trials in a highly automated manner. The detailed design and the control implementation of Uni-Form are demonstrated followed by its performance verification. The Uni-Form system is employed to study the mechanical properties of the FAST formed components and investigate the manufacturing cycle time of the FAST process in this study.

3.2 Fast light Alloy Stamping Technology (FAST)

3.2.1 The FAST concept

One of the key features of FAST is to utilize an ultra-fast heating rate during the heating stage in order to minimize the specific types of microstructure evolution that are detrimental to the post-form strength, and shorten the cycle time whilst ensuring sufficient formability.

Chapter 3 is based on the work in the paper, Luan et al., 2016, Uni-Form: a pilot production line for hot/warm sheet metal forming integrated in a cloud based SMARTFORMING platform” Proceedings of The 3rd International Conference on Advanced High Strength Steel and Press Hardening and patents (Luan et al., 2018)

Previously, most of the research on sheet metal forming technologies for aluminium alloys centres on either the forming temperature, such as different varieties of the warm and hot forming processes, or the forming speed, such as super plastic forming (SPF) of aluminium alloys, as reviewed in Chapter 2. However, studies on the heating rate for aluminium alloys, especially on the ultra-fast heating conditions are still limited (Milkereit et al., 2014; Karbasian and Tekkaya, 2010; Starink et al., 2004; Höhne et al., 2003; Höhne and Glöggler, 1989).

Differential scanning calorimetry (DSC) is commonly utilized to investigate the microstructure evolution of the aluminium alloys under continuous heating condition at different heating rates as reviewed in Section 2.2.2 (Ohmori et al., 2002). Despite the capability of DSC on detecting the fast heating process of aluminium alloys, in which the heating rate ($\dot{T}$) is generally below 10 K/s (Schawe, 2017; Osten et al., 2015; Perkin Elmer Corporation, 2013), it is widely accepted that the individual precipitation and dissolution reactions of the material microstructure shifts to higher temperature and are increasingly suppressed when the heating rate is increased (Milkereit et al., 2012; Gaber et al., 2007; Ohmori et al., 2002). The reactions during the heating process are prone to result in premature over growth in size of the precipitation particles and consume the solute atoms (Milkereit et al., 2014). The existence of such large and stable particles, such as the β phase in the Al-Mg-Si alloys, is detrimental to the post-form strength of the material, as explained by the Orowan theory (Orowan, 1948) as shown in Section 2.2.3. Meanwhile, based on the research of annealing behaviour of the aluminium alloy, a consensus can be reached that the heat treatable aluminium alloys would be significantly softened once exposed to high temperature, typically above 300°C, for a long time of the order of several hours (Rao et al., 2013). The precipitates become coarse and sufficient strength cannot be regained through the artificial ageing unless performed after the solution heat treatment (Farshidi et al., 2015). Above all, it can be deduced that the increased heating rate, to reduce the heating time, is beneficial to the post-form strength of the heat treatable aluminium alloys formed at the elevated temperatures. It is therefore advantageous if one forming process can be completed at a time prior to any reactions of the material microstructure and make use of the high forming temperature through the ultra-fast heating rate. The improved formability, high post-form strength and short cycle time can be achieved at the same time.

The precipitation reactions and dissolution reactions of the microstructure are generally associated to the exothermic and endothermic peaks in the DSC thermograms respectively. By

heating the material under different heating rate and plotting the start and end temperature of each precipitation and dissolution reaction during a continuous heating process at the specific heating rate detected by DSC in a temperature-time diagram, Osten et al. (2015) created a continuous heating precipitation/dissolution diagram for several types of Al-Mg-Si alloys with a series of heating rates from 0.01 K/s to 5 K/s.

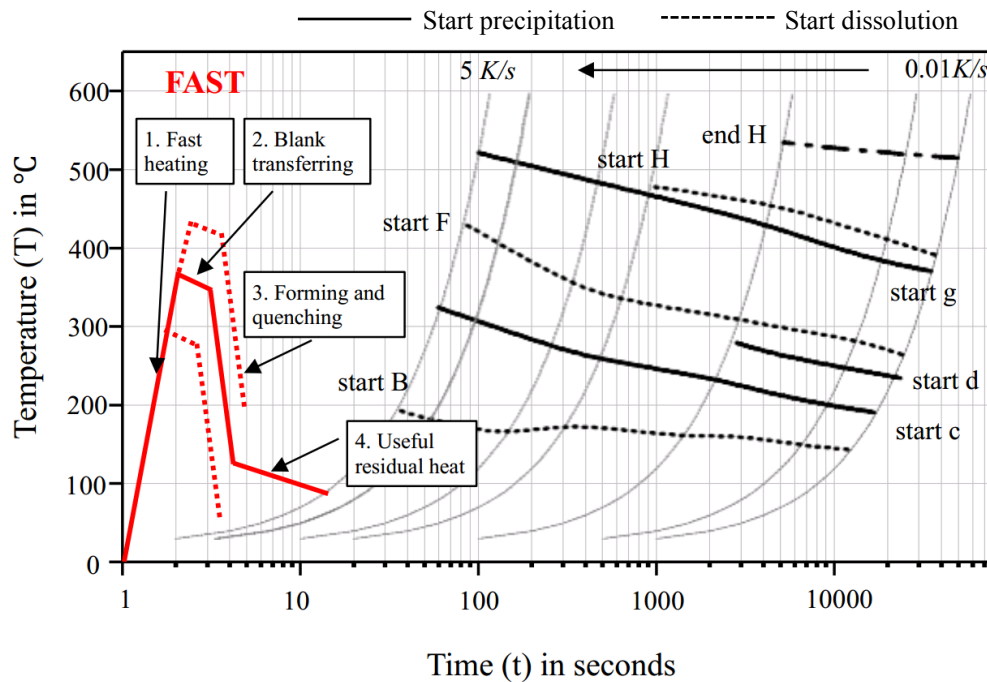


Fig 3.1 The FAST process (shown as red line), overlapped on a continuous heating precipitation/dissolution diagram of AA6082-T4 obtained from Osten et al. (2015)

Figure 3.1 is a superposed figure of the FAST process (shown as the red line) and the continuous heating precipitation/dissolution diagram of AA6082-T4. The black solid lines with lowercase letters correspond to the exothermic precipitation reactions. For example, the ‘start c’ and ‘start d’ correspond to the precipitation of β'' and the precipitation of β' respectively. Meanwhile, the black dash lines with capital letters represent the endothermic dissolution reactions of different types of particles of the material. For example, the ‘start B’ and ‘start H’ represent the dissolution of natural ageing clusters of the T4 temper material and the final dissolution of all remaining phases respectively (Osten et al., 2015).

It is theoretically feasible that neither the precipitation nor dissolution reaction is triggered at elevated temperatures for the aluminium alloy AA6082 once the ultra-fast heating and

quenching are applied and the FAST process is completed within a certain time. As a result, FAST is able to eliminate the restrictions on the forming temperature. The forming temperature is neither restricted below a certain level to prevent recovery and precipitates coarsening from happening, nor is as high as the solution heat treatment temperature (SHT) to fully solutionize the aluminium blank for high ductility and achieve high post-form strength through the subsequent artificial ageing. The forming temperature selection, as shown by the red dash line in Figure 3.1, would therefore only rely on the formability required to form the part, reducing the energy consumption and the cycle time, which is a breakthrough when compared to traditional warm and hot forming processes. Meanwhile, as recovery and precipitate coarsening which are detrimental to the post-form strength are minimized, and the existing hardening phases of the material could be preserved during the FAST process, the paint bake cycles utilized by automakers are likely to be sufficient for the material to attain its full strength instead of requiring post-form artificial ageing. The feasibility of the FAST process will be demonstrated experimentally in Chapters 4 and 5.

Compared with other sheet metal forming technologies for aluminium alloys, the features of FAST can be summarized as follows:

1. FAST takes the advantage of the material properties of AA6082 under ultra-fast heating conditions that both the precipitation and dissolution reactions tend to not be triggered and minimize the detrimental microstructure evolutions.
2. FAST provides sufficient formability of the metal blank to form complex shaped components, since the forming parameters including the forming temperature and forming speed could be pre-defined according to the complexity of the component to be formed.
3. The energy consumption and cost is largely reduced as the forming temperature is kept at a minimum level sufficient to just form the component. Also, the ultra-fast heating rate, lower forming temperature and reduced pressurized die quenching time all contribute to a shorter cycle time.
4. The elimination of artificial ageing after forming reduces the number of production steps and the required equipment, which further facilitates the efficiency and cost effectiveness.

5. The initial blank temper such as T4 and T6 can be selected and maintained throughout the process, which could reduce the unnecessary energy and time consumption for both blank manufacturers and press shops in heat treating the material, thus promoting the economic efficiency of FAST.

3.2.2 The FAST process specifications

Compared with the traditional warm and hot stamping processes for aluminium alloys, the FAST process can be completed during the incipient heating stage of these processes, as shown in Figure 3.2 (Luan et al., 2018; Sun et al., 2018; Zhang et al., 2018 (a); Zhang et al., 2018 (b); Sun et al., 2017). The process begins with heating the aluminium blank with ultra-fast heating rate over 100°C/s to the specific temperature (T_{FAST}) at which the formability of the blank is sufficient to form the component. The proprietary contact heating method is considered to be used in order to achieve the heating rate, which is significantly higher than that used in the warm forming processes employed by vehicle manufacturers (Harrison et al., 2013 (a)).

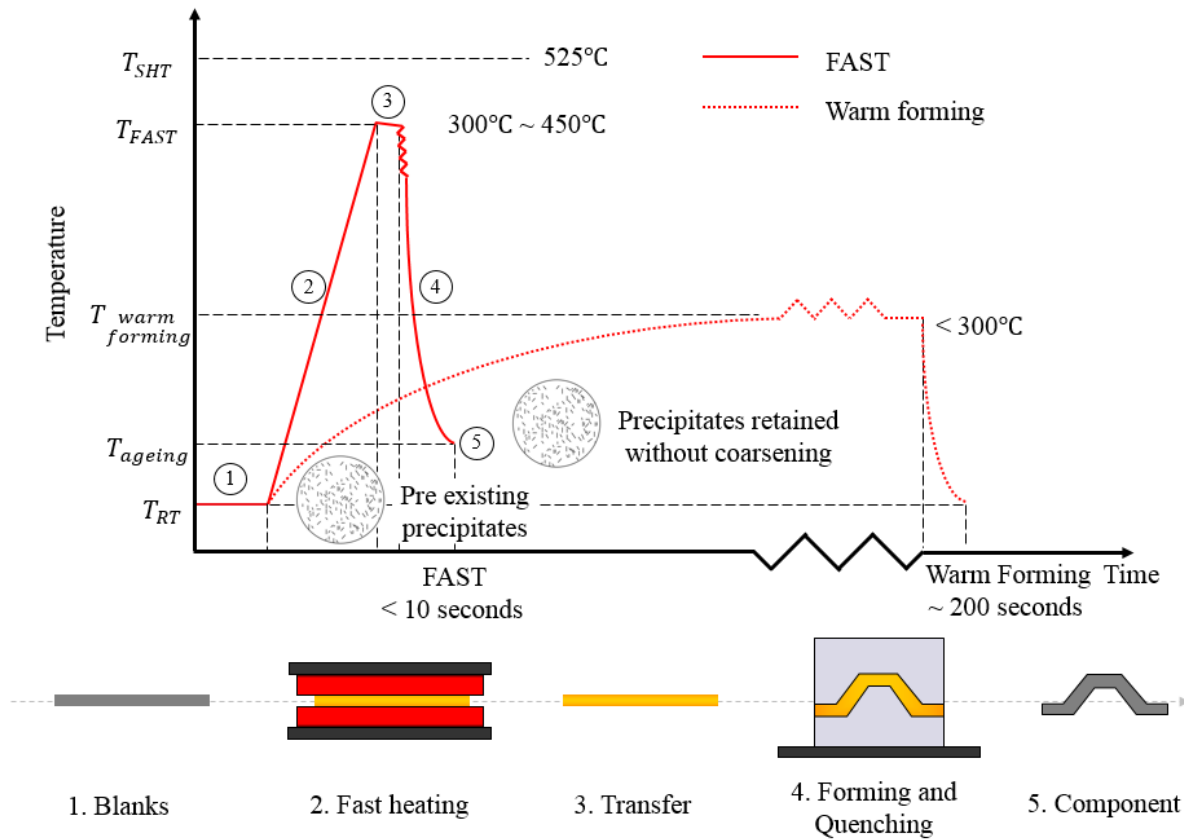


Fig 3.2 Schematic diagram of the Fast light Alloy Stamping Technology (FAST) process compared with the warm forming process

Once heated, the blank is rapidly transferred to the dies (typically within 3 seconds) and stamped. The cold forming tools are utilized to ensure the blank is quenched at sufficiently high quenching rate during the forming and quenching stage (Luan et al., 2016 (b)). The high forming speed is also applied to reduce the heat loss, maintain the temperature and therefore the formability of the blank during forming. The formed component is held in the dies under an appropriate die closing force until quenched to the precipitation hardening favourable temperature (T_{ageing} , 180°C for 6xxx series aluminium alloys) taking advantage of the useful residual heat before the paint bake cycles. In the case that the existing paint bake cycles utilized by different automotive manufacturers are not appropriate or sufficient in time and temperature for the formed component to regain its full strength, an optional incubation step of the FAST process could be applied, where the formed component would be kept in an incubation chamber for a short time (up to 5 min), facilitating the paint bake response of the component until it eventually regains the full strength through the paint bake cycles.

3.2.3 Utilization of the automotive paint bake cycles

Paint bake cycle is an indispensable procedure during vehicle production, where the panels of the vehicle are sprayed and coated with a number of layers for decoration and protection purposes (Pfanstiehl, 1998). According to different manufacturers, paint bake cycle is comprised of two to five sequential steps including the electrodeposited coating, drying the vehicle body-in-white and curing the multiple painting layers (Toda et al., 2013; Quainoo and Yannacopoulos, 2004). Altogether the paint bake cycle normally takes one to two hours with a temperature between 120°C and 200°C (Aleris Aluminum Duffel BVBA, 2012).

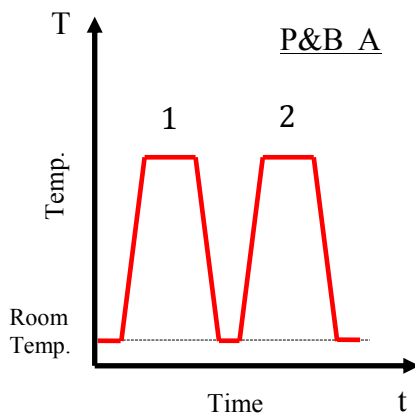


Fig 3.3 Schematic diagram of paint and bake (P&B) scheme A

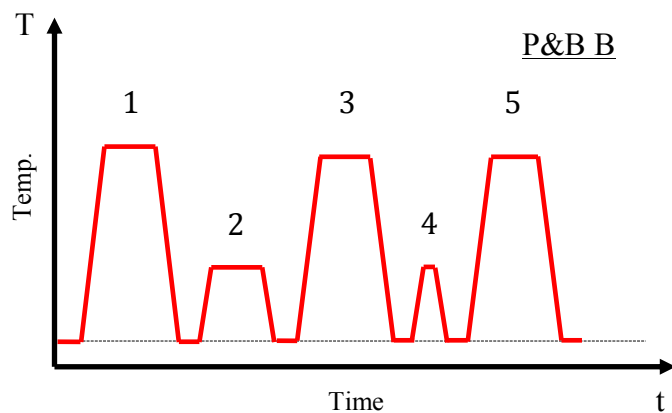


Fig 3.4 Schematic diagram of paint and bake (P&B) scheme B

The specifications of the paint bake cycle are highly confidential by the automotive manufacturers. The paint bake cycles including temperature and duration for two automakers (A and B) are shown in Figure 3.3, Figure 3.4 and Table 3.1. The paint bake cycles were incorporated into the FAST process to evaluate their effectiveness in this new process.

Table 3.1 Temperature and duration of paint and bake (P&B) schemes A and B

Type Step	P&B A	P&B B
1	180 °C, 20 min	190 °C, 30 min
2	180 °C, 20 min	100 °C, 30 min
3		180 °C, 30 min
4		50 °C, 5 min
5		180 °C, 25 min

3.3 Design and implementation of the dedicated test facility: Uni-Form

3.3.1 Concept and configuration of Uni-Form

In order to optimise the performance of the FAST process, conduct the forming trials, study the mechanical properties of the formed components and explore the effects of forming parameters, a dedicated test facility Uni-Form was developed in this study.

The flow chart of the Uni-Form design process is shown in Figure 3.5. Four objectives including ultra-fast heating, precision processing parameters control, modular design and automated & programmable were proposed. As a highly integrated test facility, it comprises of a proprietary heating device for fast heating, a precisely adjustable conveyor system for transferring the specimen, alterable forming tools, and an incubation chamber capable of performing various pre-form and post-form heat treatments.

- Furnace/heater

The most distinct feature of the FAST process is the ultra-fast heating during the heating stage. In order to achieve this ultra-fast heating rate, several heating methods were investigated and compared, including resistance heating, contact heating, traditional convection furnace, infrared heating and induction heating applied in Uni-Form (Martins et al., 2016; Dynamic System Inc, 2008; Kadolkar et al., 2004; Schmidt et al., 2003).

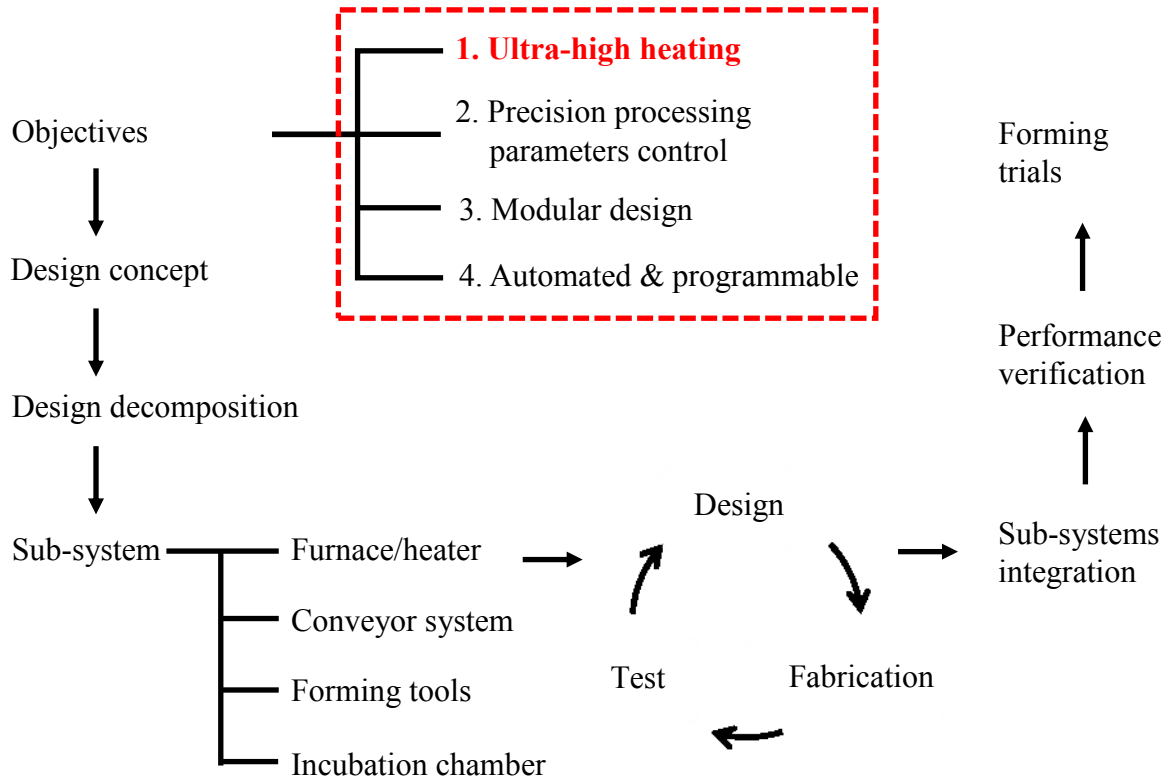


Fig 3.5 Flow chart of the Uni-Form design procedure

A decision matrix on the furnace/heater selection was conducted as shown in Table 3.2. Eight key factors were considered including heating rate, temperature distribution uniformity, ease of integration into a production line, cycle time/complexity for experiment, blank geometry /flexibility, material applicability, energy efficiency and cost effectiveness. Each criterion and its weighting were determined by considering its importance to the FAST process, ease of implementation for automakers and international standards of evaluation of machine tools (Bassan, 2019; ISO, 2019; ISO, 2018; Luan et al., 2018 (b); Qin, 2016). Consequently, it was gathered from the high heating efficiency, adjustable size of the apparatus and ease of integration into the system that contact heating in the form of platen heaters would be the optimal heating scheme for Uni-Form.

- Conveyor System

The total cycle time of FAST must be kept within 10 seconds with precise control of the transfer time and specimen's positioning, which presents a challenging requirement for the specimen's transferring system. Therefore, three automated handling systems were investigated for the Uni-

Table 3.2 Design decision matrix of the heating methods

Selected criteria	Weight	1. Resistance Heating		2. Contact Heating		3. Convection Furnace		4. Infrared heating		5. Induction Heating	
		Score 10/10	Weighted	Score 10/10	Weighted	Score 10/10	Weighted	Score 10/10	Weighted	Score 10/10	Weighted
Heating rate	25%	10	2.5	9	2.25	3	0.75	6	1.5	7	1.75
Temperature distribution uniformity	20%	5	1	10	2	9	1.8	8	1.6	8	1.6
Ease of integration into a production line	15%	10	1.5	8	1.2	6	0.9	9	1.35	8	1.2
Cycle time / complexity for experiment	15%	10	1.5	8	1.2	4	0.6	5	0.75	6	0.9
Blank geo. / flexibility	10%	3	0.3	7	0.7	10	1	8	0.8	6	0.6
Material applicability for aluminium alloys	5%	8	0.4	10	0.5	10	0.5	6	0.3	7	0.35
Energy efficiency	5%	10	0.5	6	0.3	4	0.2	8	0.4	8	0.4
Cost effectiveness	5%	10	0.5	6	0.3	4	0.2	7	0.35	7	0.35
Total weighted score	100%	8.2		8.45		5.95		7.05		7.15	
Rank (with weighting)		2		1		5		4		3	

Explanation Notes:

1. Score on each criteria of a particular heating method is ranked from 1 to 10, with 10 as highest
2. Weight of each criteria is ranked from 5% to 25%, with 25% as the most important aspect of heating method used in FAST.
3. The total score without weighting is a simple addition of all scores together.
4. The total score with weighting is an addition of all weighted individual scores.

Table 3.3 Design decision matrix of the conveyor system

Selected criteria	1.Robotic Arm Universal Robots UR 10	2.Linear Speedfeeder AP&T speedfeeder 40/60 T2	3.Conveyor System Dorner 2200 Precision Move
Grip and Movement of the blank	Risk of drop/deformation	Risk of drop/deformation	No drop/deformation
	Requires active clamping end-effector	Requires active clamping end-effector	Rests upon conveyor with constant, light contact
Positional Accuracy	Low	High	High
	Multi-degree movement, each with tolerances	Three dimensional linear movement	One dimensional movement
Simplicity of Control	Low	Medium	High
	Multi-degree movement to be programmed, as well as end-effector	Three dimensional linear movement with end-effector programming	One dimensional motion with no end-effector
Ease of Integration	Difficult	Easy	Medium
	For linear motion, very large working envelope required	Configurable system lengths, single sided carriage	Configurable system lengths, however two conveyors are necessary for balance
Cost	High	Medium	Medium
	>£10,000	~£5,000	~£5,000

Form, namely the robotic arm (Universal Robots UR 10), the linear speedfeeders (AP&T SpeedFeeder 40/60 T2) and the conveyor System (Dorner 2200 Precision Move). A design decision matrix had been made as shown in Table 3.3. The belt conveyor was selected considering the high positional accuracy and simplicity of control.

- Forming tools

The forming tools should be designed as a modular sub-system, where the die and punch can be altered as requested with relative ease. This could add the options of conducting forming

trials for components with different geometries. In the present study, as shown in Figure 3.7, U-shape forming tools were used to enable the study of formability and post-form springback.

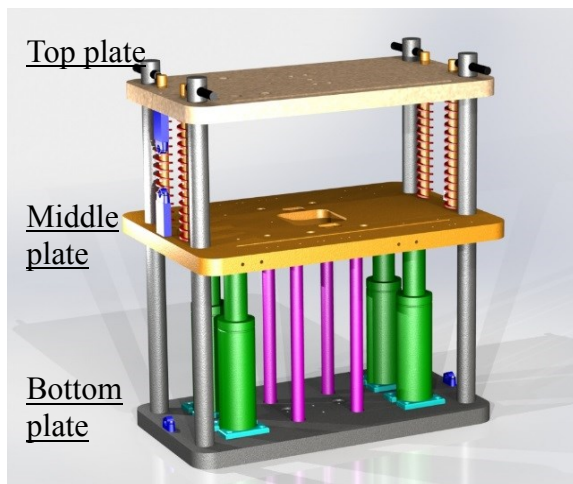
- Incubation Chamber

The incubation chamber is designed to offer a soaking environment ranging from 90 to 250°C for the required duration according to the specific heat treatment and paint bake cycles. Feedback control on temperature and time is required. In addition, the incubation chamber needs to have adequate thermal insulation to ensure the efficiency of various heat treatments. Multiple-layered insulation materials could be used to reduce the exposure of the chamber to the external conditions.

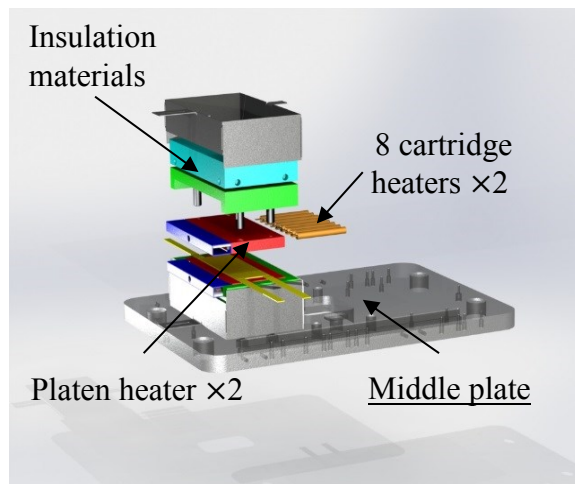
With the four integrated sub-systems, Uni-Form aims to be controlled and programmed remotely through a connected computer or by being integrated into a cloud-based online platform. The system was designed to be a fully functional and closed-loop sheet material forming research system, covering different warm and hot forming processes including FAST in an intelligent and precise manner.

3.3.2 Detailed design of Uni-Form

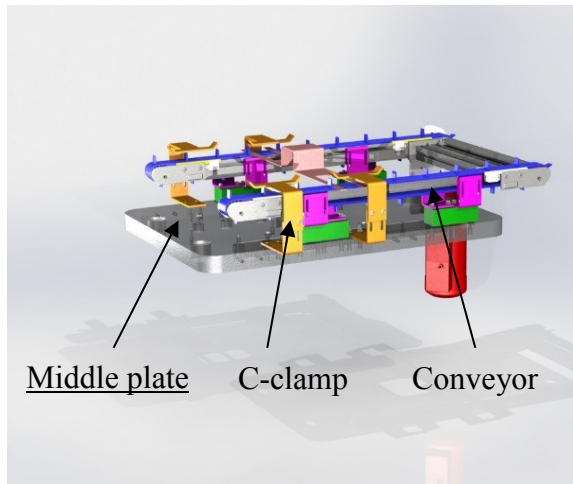
The dedicated pilot production line Uni-Form was designed and fabricated, following the concept and configuration described in the previous section. The assembly designs of Uni-Form, in the form of four main parts, namely the frame, the contact heater, the belt conveyor and the incubation chamber, are shown in Figure 3.6.



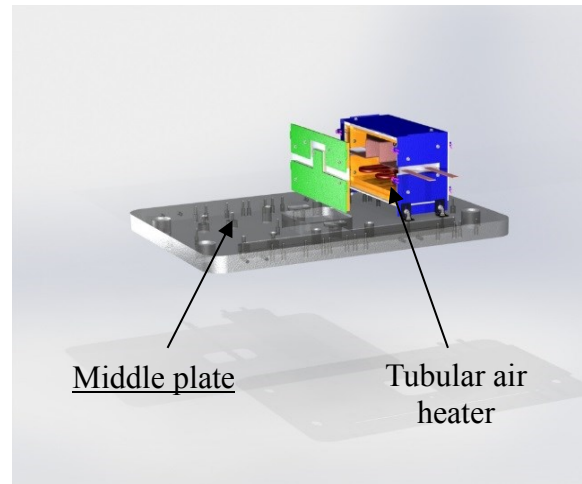
(a)



(b)



(c)



(d)

Fig 3.6 Design of the four main parts of Uni-Form (a) the frame, (b) the platen heater, (c) the belt conveyor and (d) the incubation chamber

The forming tools installed in Uni-Form are shown in Figure 3.7 including the die, punch and blank holders. The overall design of Uni-Form is shown in Figure 3.8 and the assembled Uni-Form is presented in Figure 3.9.

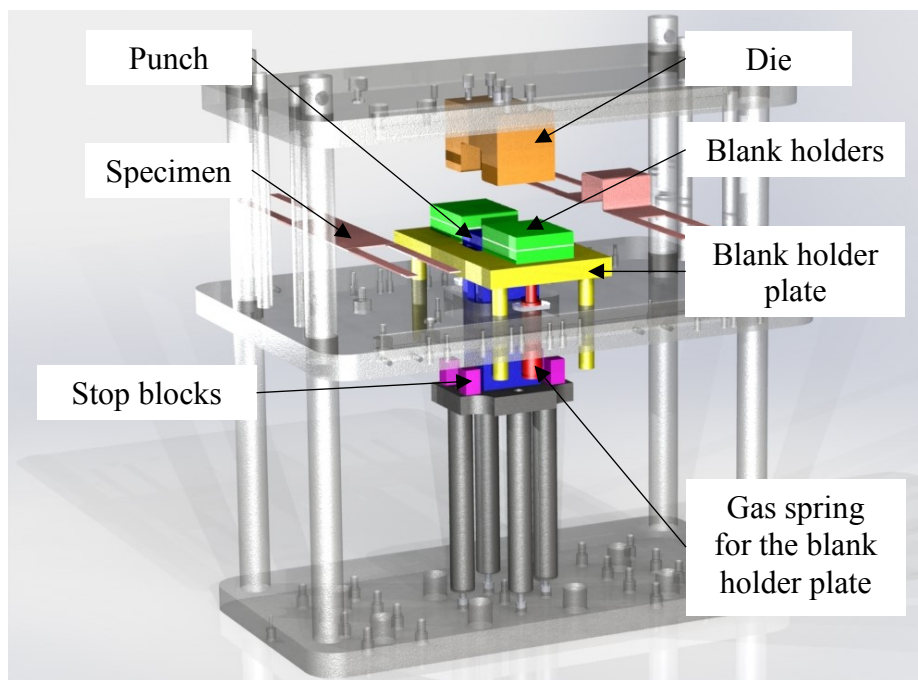


Fig 3.7 Design of the forming tools of Uni-Form

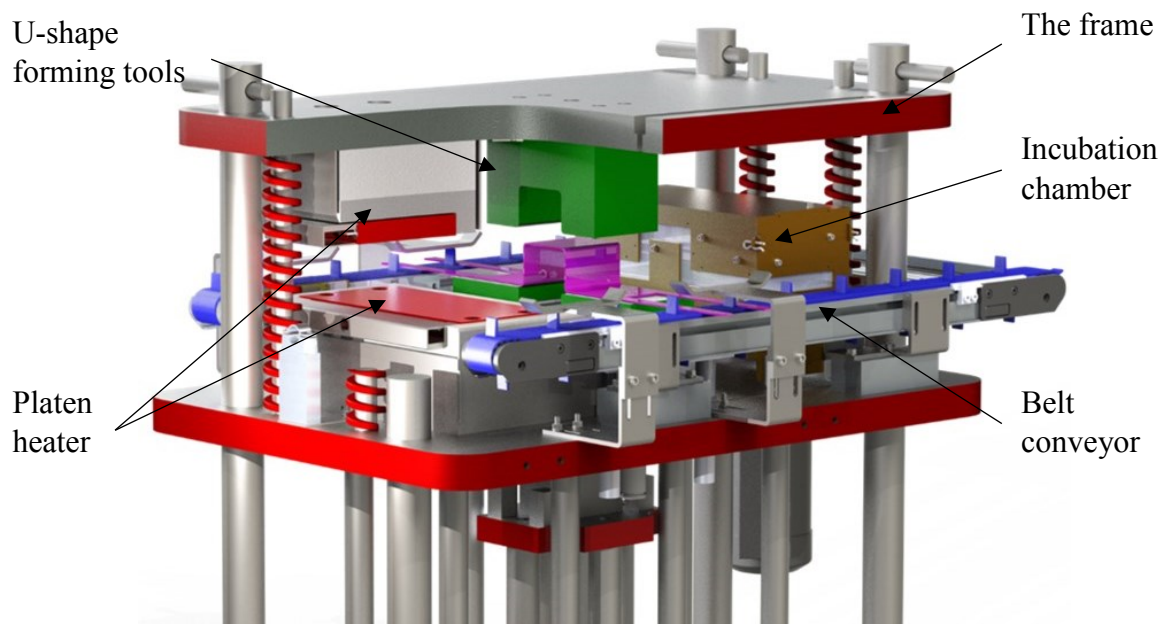


Fig 3.8 The overall design of Uni-Form

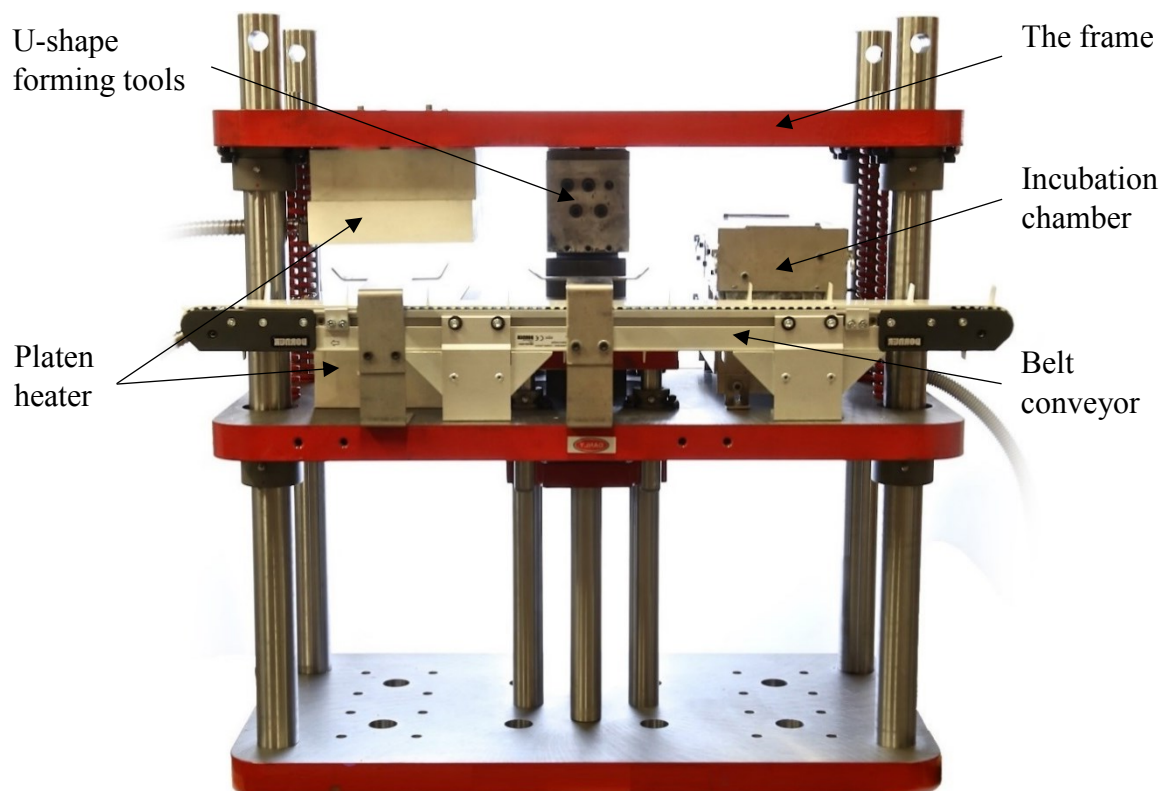


Fig 3.9 Uni-Form with all parts assembled on the frame

The frame of Uni-Form accommodates all the sub-systems, exposing them to the correct forces while holding them in place with sufficient positional accuracy. As shown in Figure 3.6 (a), the frame consists of three plates, which are made of EN25 high carbon steel. The middle plate can be supported either by the gas springs of the cushion system below the Uni-Form via extended pillars as shown in Figure 3.10 or by independent gas springs installed on the bottom plate of Uni-Form, which can be seen in Appendix 1 (a).

As shown in Figure 3.6 (b), two conductive platen heaters were installed on the top plate and middle plate of Uni-Form respectively. Eight high performance cartridge heaters (350 watts each) were embedded in each platen heater. A maximum temperature of 650°C and a fast heating rate over 100°C/s could be implemented. The position of the cartridge heaters were defined by a series of thermal analyses to ensure the temperature uniformity. In addition, a combination of the insulation materials Duratec 750 Machinable Ceramic and PROMALIGHT 1000X-HD insulation board were applied to insulate the platen heaters offering an extremely low thermal conductivity of around 0.030 W/m · K to prevent heat loss. A conservative heat flow scenario of the entire insulation module at the maximum operating temperature was run using PROMAT software and yielded a temperature of 45°C on the bottom of the furnace, which was considered safe in use.

The conveyor was installed on the middle plate of Uni-Form, as presented in Figure 3.6 (c). In order to prevent the specimen adhering to the top platen heater during heating or being stuck in the die after forming, two pairs of C-clamp were installed and aligned with the heaters and forming tools respectively. The incubation chamber was designed to be structurally independent of Uni-Form, as shown in Figure 3.6 (d). A tubular air heater was utilized, which is capable of reaching 650°C. The housing of the incubation chamber was made of double-layered Firefly Millboard FF700 for heat preservation. A Type-K temperature probe which contacted the formed components inside the chamber was employed for the temperature feedback control. The forming tools of Uni-Form allow for interchangeable punch and die and an adjustable blank holding force. The die and punch were installed on the top and bottom plate of Uni-Form respectively. A pair of blank holders was installed on the blank holder plate, which was supported by two gas springs (DANLY CE750×40) assembled on the middle plate, as shown in Figure 3.7. The blank holding force was 10 kN in total and verified by the FUJIFILM PRESSCALE pressure test paper, as shown in Appendix 1 (b).

This pilot production line was installed on a gas spring cushion system, as shown in Figure 3.10. This cushion system was designed to provide adjustable supporting force to the installed forming tools and for the protection purposes. The 28 individual gas springs of the cushion system could be charged to pressure between 10 and 40 bars, realizing the adjustable stamping force. In this study, the middle plate of the Uni-Form was supported by 8 extended pillars, which were directly connected to the 8 gas springs and provided the contact pressure of the platen heaters during the heating stage as highlighted in Figure 3.10. The rest of the gas springs were utilized to support the bench of the cushion system and the Uni-Form, providing the die closing pressure. In this study, the cushion system was charged to 20 bar and the whole system was assembled in a 100 tonne hydraulic press. The Uni-Form in operational condition are presented in Figure 3.11 (a) and (b). The layout of the cushion system is further explained in Section 4.2.4. The detailed assembly and installation of Uni-Form on the cushion system can be found in Appendix 1 (c).

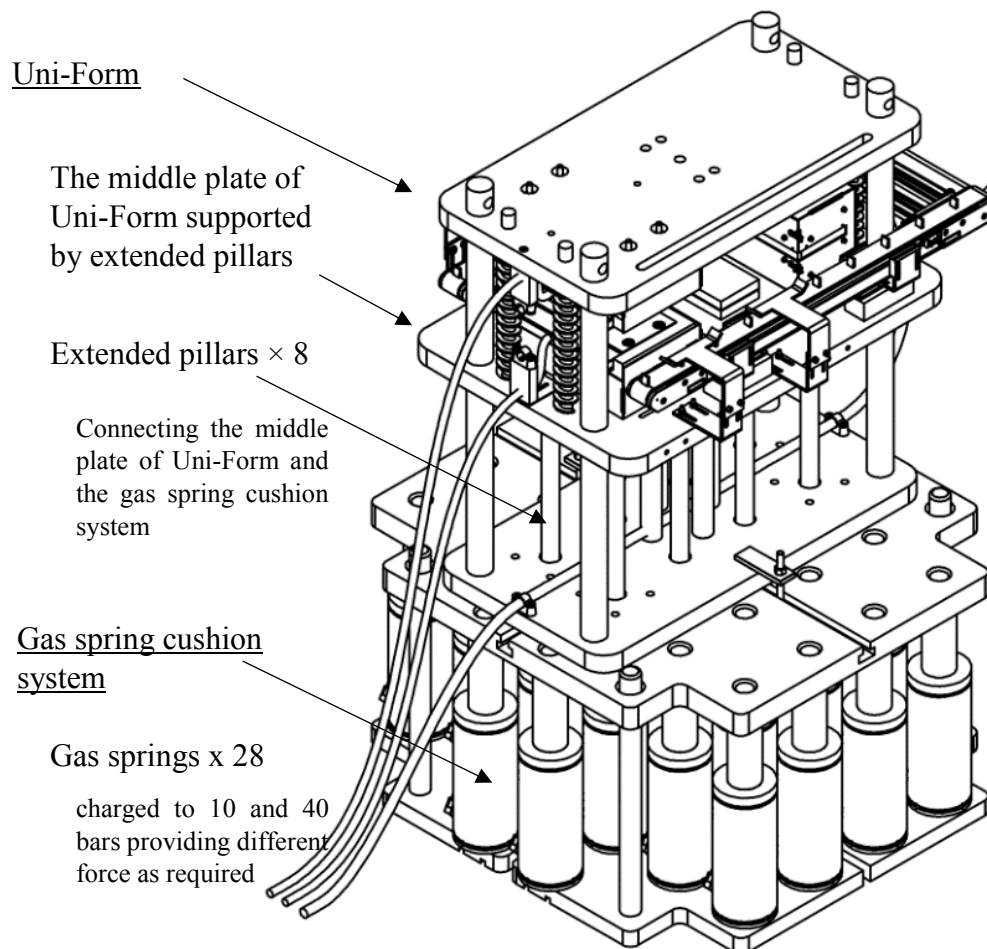


Fig 3.10 Design of Uni-Form installed on the gas spring cushion system

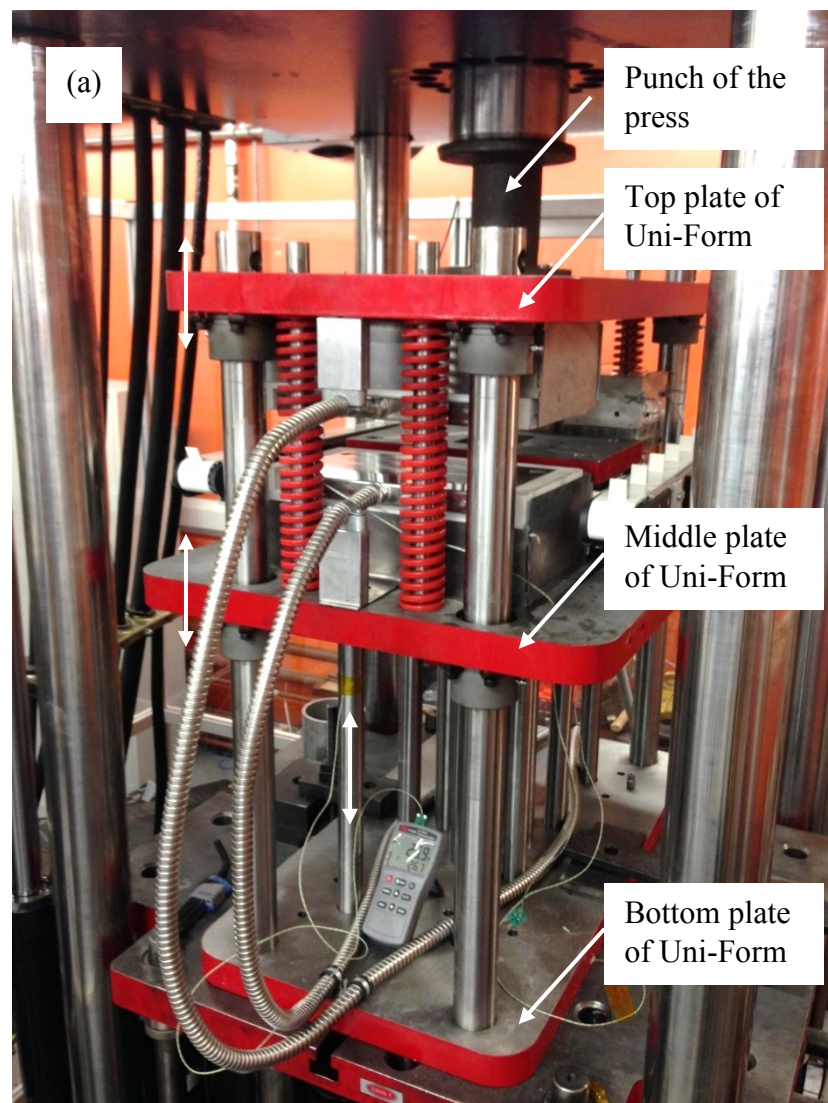


Fig 3.11 Uni-Form installed on the gas spring cushion system in the press

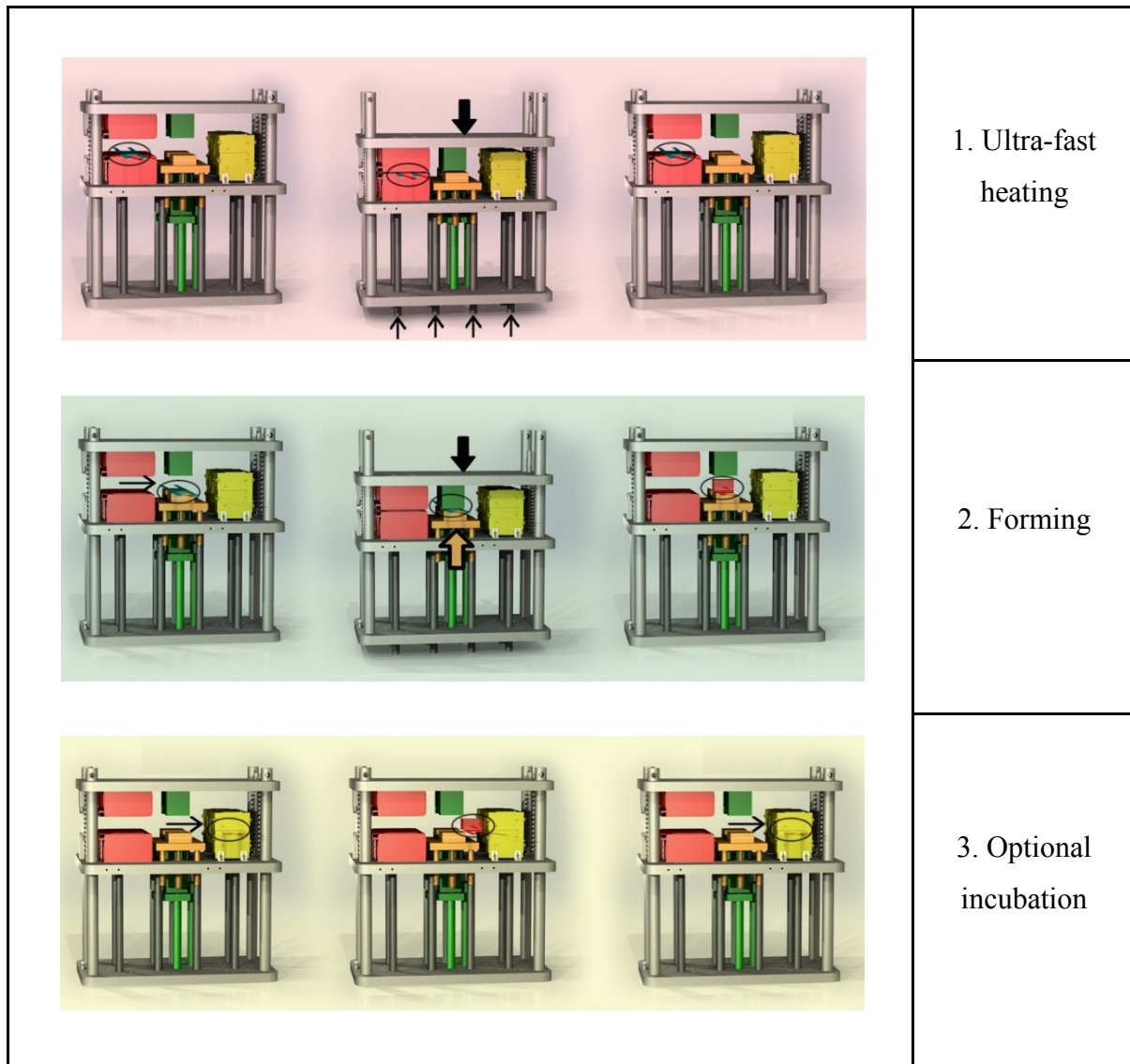


Fig 3.12 The three main periods in a typical FAST forming trial using Uni-Form

The steps of conducting the FAST forming trials using Uni-Form are as follows (Figure 3.12):

1. The forming parameters such as the forming temperature, soaking time, transfer time, heat treatment time, heat treatment temperature, heat treatment cycles are defined in the control program
2. The forming program is uploaded to the control unit of Uni-Form through a connected computer or using the online platform
3. The press on which Uni-Form is installed is switched on
4. The specimen is placed on the conveyor
5. The “START” button is pressed on the control panel of Uni-Form

6. The FAST forming trial is conducted automatically following the defined forming route:
 - 6.1 The incubation chamber heats to the pre-set working temperature and switches to standby
 - 6.2 The specimen is transferred by the conveyor system to the centre of the platen heater
 - 6.3 The press is triggered and the specimen is pressed between the two platen heaters and heated rapidly to the target temperature
 - 6.4 Once the specimen reaches the target temperature, the press releases and the specimen is transferred to the forming tools immediately
 - 6.5 The alignment of the specimen and the forming tools is achieved accurately by the conveyor system
 - 6.6 The press stamps the specimen into the required shape with desired speed (100 mm/s - 400 mm/s) and pressure (10 MPa - 20 MPa)
 - 6.7 The formed specimen is held in the dies for a pre-set duration (1.0 second - 4.0 seconds) and then the press is released
 - 6.8 The conveyor transfers the formed piece into the incubation chamber
 - 6.9 A temperature sensor contacts the surface of the formed piece and enables the feedback control of the incubation chamber
 - 6.10 The temperature of the incubation chamber is calibrated following the defined heat treatment scheme
7. Once the heat treatment is completed, the indicator light turns on and the specimen is transferred back to the start position

An “Emergency Stop” button is embedded into the control system for health and safety considerations. If the button is pressed, the press releases and stops, the conveyor system transfers the blank back to the start position, the platen heaters and incubation chamber would be turned off.

3.3.3 Control implementation and the on-line connection of Uni-Form

The Uni-Form system is controlled using the embedded C-code through a standard micro-controller PIC4331 and programmer PICKIT3, as shown in Figure 3.13. The control logic of the whole system is presented in Table 3.4. Three devices, namely the conveyor, the press and

the incubation chamber are connected and work harmoniously to realize the full functions of Uni-Form in an automated way.

The belt conveyor is controlled by Lenze Variable Speed Controller (LVSC) which offers the DC terminal strip control. The working parameters, such as top speed, acceleration, DC break time of the belt conveyor are measured by manual commissioning. The accurate timing of the belt conveyor transferring metal blanks between different stages are defined in the control program. Two pins of the microcontroller are assigned as outputs to LVSC and generate signals of 5V 20mA to realize the start and stop of the conveyor. Similar to the control of belt conveyor, another two pins are connected to the control unit of the hydraulic press, Phoenix α . Through the short pulse signals, these two pins act as the fire button and reset button of the press.

The incubation chamber temperature and time are programmed using a RS-485 serial communication interface. The temperature probe contacts the formed component in the incubation chamber and provides the temperature feedback control. A customized control program is made to adjust the power and working time of the heaters in the incubation chamber to realize the temperature adjustment. In addition, the belt conveyor is correlated with the incubation chamber enabling the formed component to move in and out following the predefined heat treatment cycles. The layout of the combined control system is shown in Figure 3.14. The arrangement of the input and output pins of the microcontroller is shown with additional details in Appendix 1(d).

The Uni-Form is further merged into a multi-objective on line platform SMARTFORMING (www.smartforming.com) as a functional module, as presented in Figure 3.15 (Luan et al., 2016 (c)). Taking advantage of cloud computing, the SMARTFORMING platform enables engineers from each industry sector to develop efficient and cost effective processing routes and to guide the implementation of the FAST process jointly. Through the online portal www.smartforming.com, multiple users can log in to the platform, work simultaneously and remotely. The different modules of the SMARTFORMING can either work individually or be linked together, such as ‘Uni-Form’ and ‘Tailor’. For example, given the geometry, category of the aluminium alloys and expected post-form strength of a formed aluminium alloy sheet metal component, the processing route for such a component including the forming temperature, forming speed, transfer time and artificial ageing parameters, can be optimized by the module ‘Tailor’. These parameters would be transferred to the control unit of Uni-Form and the forming trials can be conducted automatically.

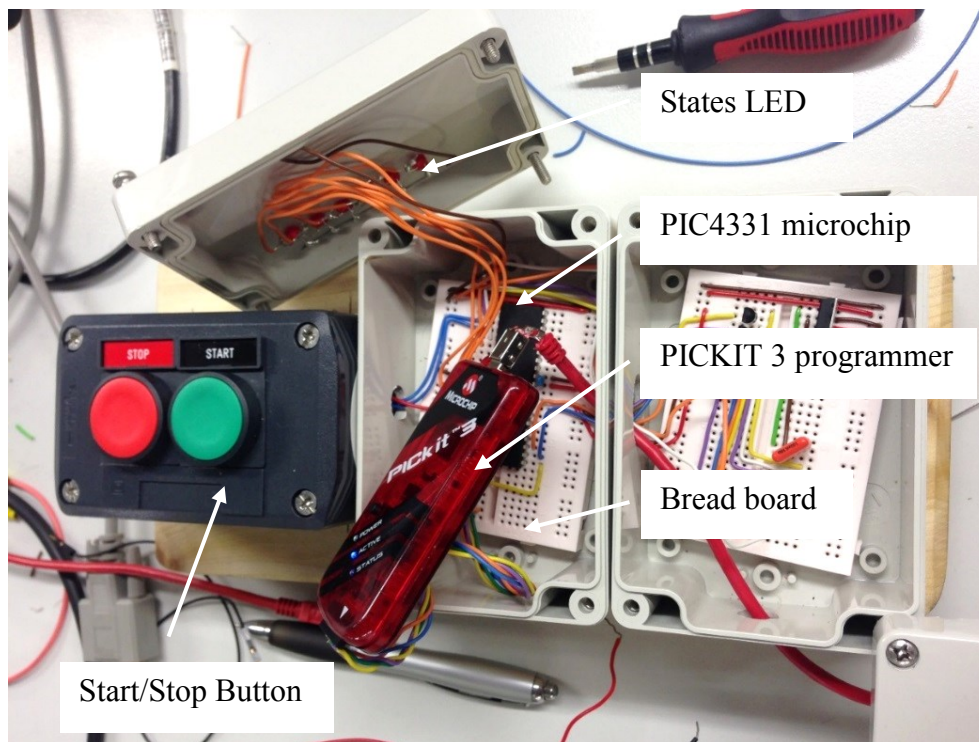


Fig 3.13 The control unit of Uni-Form

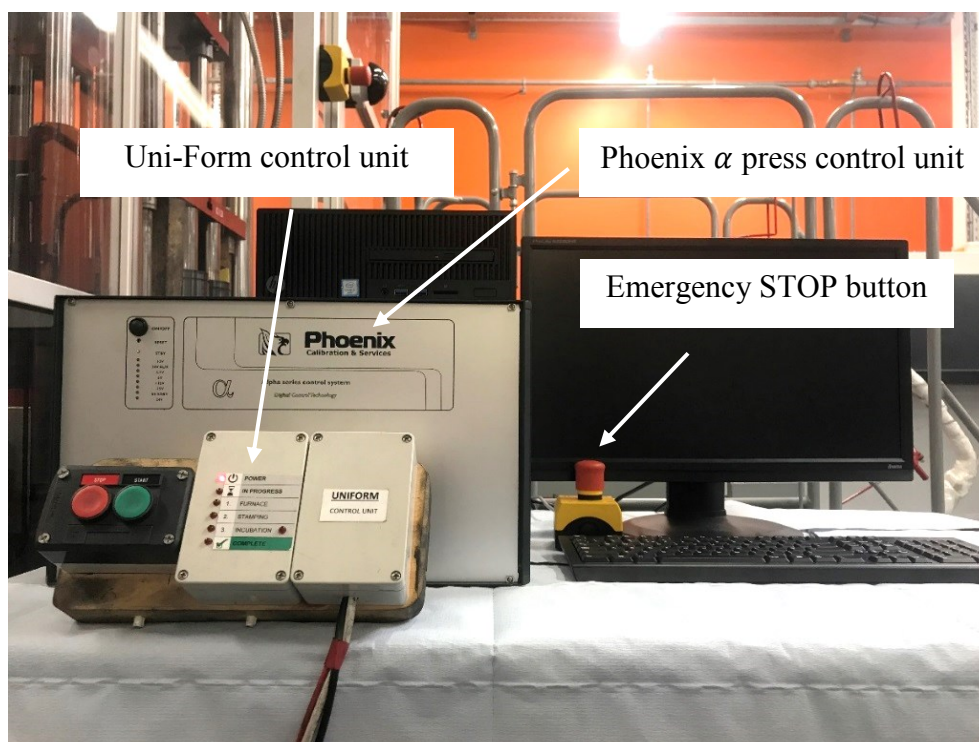


Fig 3.14 The layout of the combined control system

Table 3.4 The control logic of Uni-Form

FAST							
	Loading stage		Heating stage	Transfer Stage	Stamp Stage	Transfer Stage	Complete stage
Inputs	Load the blank	Start	Timer ends	Timer ends	Timer ends	Timer ends	Unload the blank
Microcontroller	Standby	 Loading Timer	Furnace Timer	Conveyor timer	Stamping timer		Standby
1. Stamp control	Standby	Standby	Fire	Reset	Fire	Reset	Standby
2. Conveyor control	Belt stops	Belt works	Belt stops	Belt works	Belt stops	Belt works	Belt stops
3. Furnace control	On	On	On	On	On	On	Standby
4. Incubation control	Standby	Standby	Standby	Standby	Standby	Standby	Standby

Incubation (Option)		
Incubation stage		Complete stage
Program load	Timer ends	Unload the blank
Incubation timer		Standby
Reset	Reset	Standby
Belt works	Belt work	Belt stop
Standby	Standby	Standby
On	On	Standby

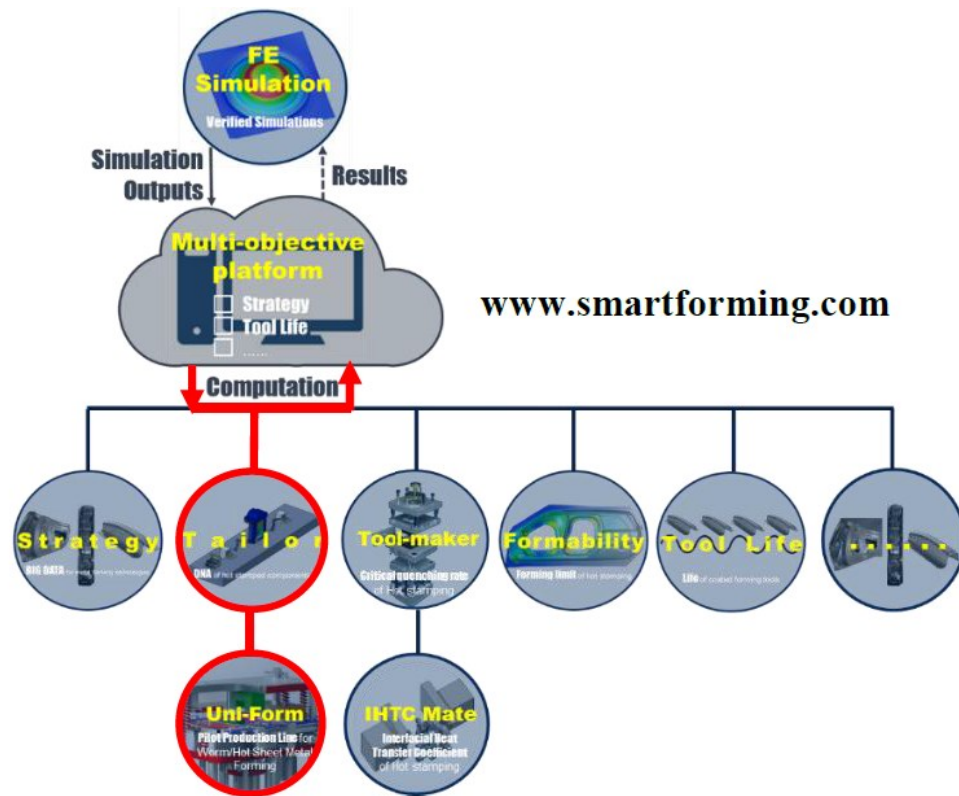


Fig 3.15 The structure of Uni-Form integrated into the multi-objective platform SMARTFORMING (Luan et al., 2016 (c))

3.3.4 Performance verification of Uni-Form

A series of performance tests of Uni-Form have been designed and conducted to verify the key specifications especially the ultra-fast heating by platen heaters and the automated heat treatment cycles by the incubation chamber and belt conveyor have been achieved as designed. The test codes follow the British standards on machine tools operating test (British Standard, 2012; British Standard, 2007). The tests were initiated from the cold run of the individual sub-system including a full run-through of the belt conveyor capabilities, frame motion analysis, press and conveyor system synchronisation tests followed by the warm run of the platen heaters and the incubation chamber independently and finally the automated forming trials with all sub-systems involved.

The conveyor showed no slippage, sagging or deformation of the specimen during transfer. According to 20 trials of different multiple stage processes, the delay of the conveyor between full speed and start/stop was on average 0.23 ± 0.2 seconds and the blank stop position varied

within 1 mm in each trial, which confirmed the repeatability and high positional accuracy of the conveyor. Frame motion tests of Uni-Form confirmed the top and middle plates moved as intended and the platen heaters and forming tools withstood the force/moment associated with the press. No interference between different components of Uni-Form were found during the tests.

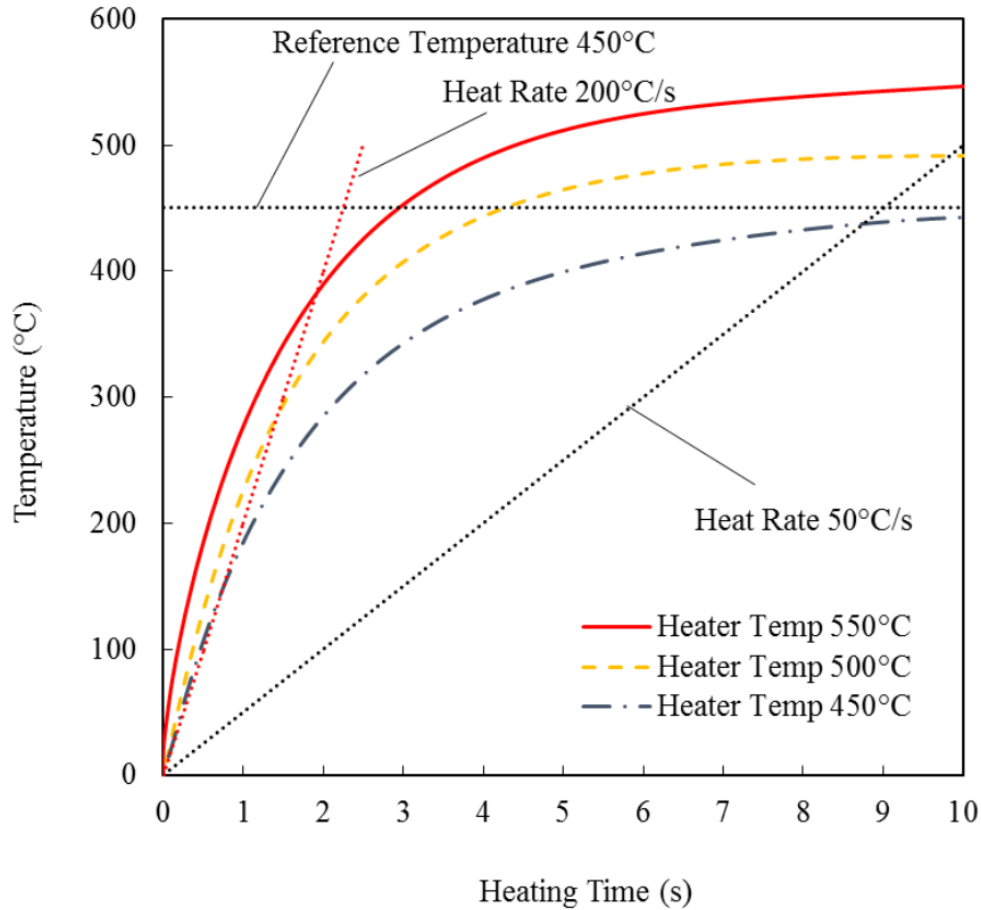


Fig 3.16 Heating rate of Uni-Form with different platen heater temperatures and the gas spring cushion system charged to 20 bar

The performance of the platen heaters of Uni-Form was measured and calibrated through a series of heating tests. The influence of contact pressure and platen heater temperature was investigated. As shown in Figure 3.16, the average heating rate with accurate heating temperature control is over 100°C/s and more than 200°C/s at the initial heating stage when the gas spring cushion is charged to 20 bar and the heater temperature is 550°C. In addition, the temperature uniformity of the platen heater was verified through measuring the temperature

evolution at different positions on the heater. It has been proved that the temperature difference between the centre and edge of the heater was within 5%. The temperature profiles for different platen heater temperatures and the contact pressures between the blank and platen heaters were recorded in the control program of Uni-Form to facilitate the heating parameter selection.

The multi-cycle heat treatments using the incubation chamber were also verified. Three sets of paint bake cycles were programmed, namely 100°C for 15 minutes, 180°C for 15 minutes and 220°C for 15 minutes covering the main range of heat treatment temperature for the 6xxx series aluminium alloys. A U-shape component was loaded on the conveyor and moved in/out from the incubation chamber following the defined heat treatment cycles. Three different positions namely the top surface, the edge and the sidewall of the component were attached with Type-K thermocouples recording the temperature evolutions during the test.

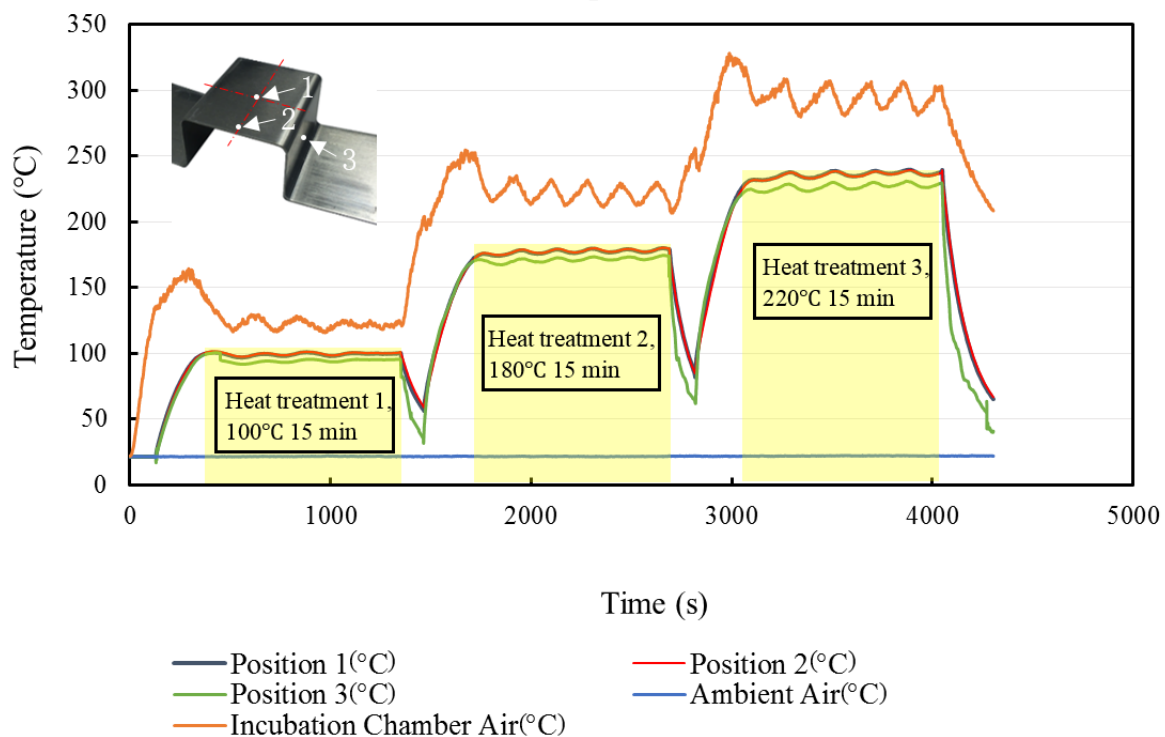


Fig 3.17 Temperature of the three locations in the incubation chamber under three different paint bake cycles

As shown in Figure 3.17, the temperature history of the three positions are almost identical, demonstrating a homogeneous temperature distribution of the formed component during the heat treatment. Moreover, the temperature measured on the specimen correlates well with the

defined heat treatment cycles, illustrating the temperature of the incubation chamber can be adjusted intelligently and the belt conveyor can move the specimen as programmed in a fully automatic way.

3.4 Summary

In this chapter, a novel sheet metal forming technology, Fast light Alloy Stamping Technology (FAST) is proposed in light of the industrial needs and the improvement of the existing sheet forming technologies for aluminium alloys. Through the comparison of the temperature evolution of FAST and the continuous heating precipitation/dissolution diagram of several typical Al-Mg-Si alloys, it was found feasible that the precipitation and dissolution reactions of the material microstructure could avoid being triggered at elevated temperatures through the ultra-fast heating and quenching. Compared with the traditional warm and hot stamping processes, the FAST process can significantly save the cycle time and allows for full flexibility in the forming temperature selection. As the recovery and the precipitates coarsening are minimized and the existing hardening phases of the material could be preserved during the process, the paint bake cycles utilized by automakers are likely to be sufficient for the material to attain its full strength instead of the post-form artificial ageing.

A dedicated pilot production line Uni-Form was developed to enable the forming trials of the FAST process. The system consists of four main parts: the frame, the platen heaters, the belt conveyor and the incubation chamber. Through the programmed microcontroller, Uni-Form is capable of conducting the forming trials in a highly automated way. The platen heaters provide an ultra-fast heating rate over 100°C/s and more than 200°C/s at the initial heating stage. The incubation chamber could realize multi-cycle heat treatments with accurate temperature control and uniformity of the components.

Chapter 4

Experimental programme of the FAST process study

4.1 Introduction

In this chapter, the experimental tests that were designed and conducted to study the FAST process on aluminium alloy AA6082 are presented. Firstly, the precipitation hardening behaviour of AA6082 was investigated through natural ageing tests and artificial ageing tests under different ageing time and temperatures. Secondly, the heat treatment tests following the FAST process were conducted to demonstrate proof-of-concept and study the performance of this forming technology. The effects of the material temper and forming temperature of the FAST process were investigated. In addition, comparison tests, in which the specimens were heat treated following warm and hot stamping processes with slow heating rate were conducted. Paint bake cycles were applied to all the specimens after testing in order to explore the effects of such post-form heat treatment on FAST and other forming processes. Transmission electron microscopy (TEM) scans were performed on the specimens to gain an understanding of the microstructural mechanisms involved in the FAST process. The thermo-mechanical properties of AA6082 under the ultra-fast heating conditions were also studied through uniaxial tensile tests. Thirdly, forming trials of FAST were performed on the dedicated test facility Uni-Form. A range of forming conditions including forming temperatures, forming speeds and material tempers were tested in order to explore these effects on the mechanical properties of the formed components. Furthermore, a benchmark study on the cycle time was conducted to analyse the influence of different forming stages on the production efficiency of FAST and other sheet metal forming processes.

4.2 Test material and test facilities

Chapter 4 is based on the work, Luan et al., 2016, Characterization of the interfacial heat transfer coefficient for hot stamping process, Journal of Physics; Conference Series, 734 and co-authored work, Zhang et al., 2018 (b), Investigating the quench sensitivity of high strength AA6082 aluminium alloy during the new FAST forming process, Proceedings of IDDRG2018 – 37th IDDRG conference Materials Modelling and testing for sheet metal forming

4.2.1 Test material

The material used in this study was commercial sheet aluminium alloy AA6082-T6 with a thickness of 1.5 mm, provided by AMAG Austria Metal AG. The composition of the material as received is shown in Table 4.1. The geometry of the initial blank is 800 x 600 mm and the Vickers hardness is 116 ± 2 Hv. All the blanks were from the same batch and the specimens were manufactured by laser cutting with their longitudinal direction parallel to the rolling direction of the blank, as shown in Figure 4.1.

Table 4.1 The chemical composition of AA6082-T6 (AMAG, 2013)

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Wt %	0.7-1.3	0.5	0.1	0.4-1.0	0.6-1.2	0.25	0.2	0.1	Balance

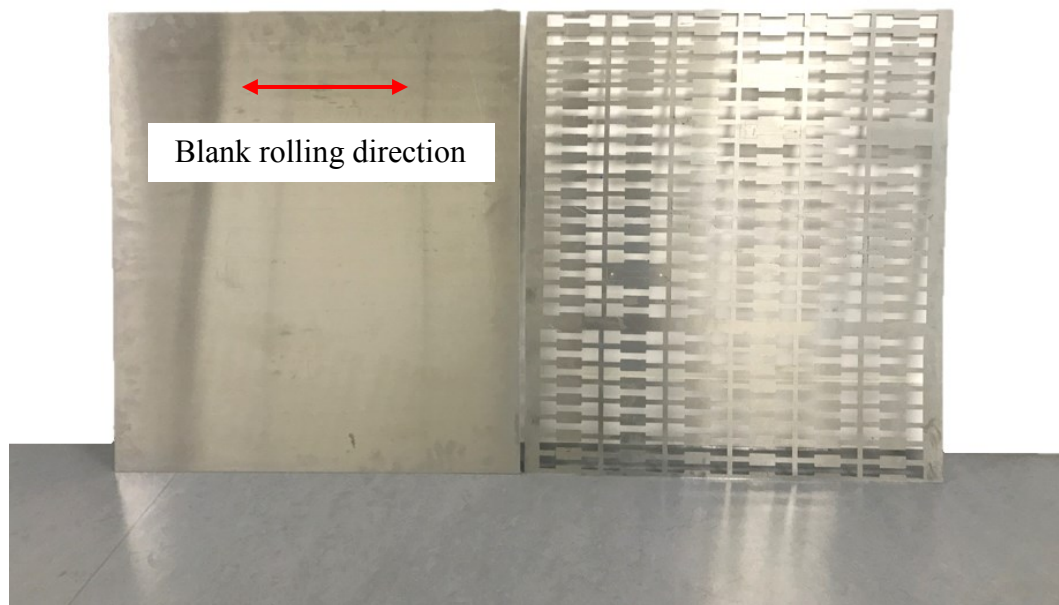


Fig 4.1 The as-delivered AA6082-T6 blank before (left) and after (right) laser cutting

4.2.2 Gleeble 3800 thermal-mechanical test system

The Gleeble 3800 thermal-mechanical simulator was used in this study, as shown in Figure 4.2. As a highly integrated test facility, Gleeble comprises three main systems: the heating/cooling system, the mechanical tension/compression system and the digital control system. Through

electrical resistance heating, the Gleeble 3800 is able to achieve a heating rate of up to 10,000°C/s and maintain the steady-state temperature of the specimen during the test. The embedded cooling channels in the jaws and the separate quenching apparatus which use compressed air/water can apply sufficient cooling to the specimen (Dynamic System Inc, 2008). Therefore, the temperature evolution of the specimen can be accurately defined and controlled. A pair of jaws are installed in the test chamber, one of which is fixed and the other moves forwards and backwards with a tension force of 98.1 kN and a compression force of 196.2 kN. The applied load is measured by the load cell within the jaw. The ram speed of the moveable jaw is up to 2 m/s with a total stroke of 150 mm, enabling a large range of strain and strain rates to be tested. For the uniaxial tensile tests, the C-Gauge is used to record the deformation of the specimen through measuring the variation of the width of the specimen at its centre, as shown in Figure 4.3.



Fig 4.2 Gleeble 3800 system



Fig 4.3 C-Gauge

4.2.3 IHTC-mate

The heat treatment tests following the temperature profiles of the FAST process and other hot and warm forming processes were conducted on the dedicated test rig IHTC-mate (Luan et al., 2016 (b)), as shown in Figure 4.4. This test rig is designed to be integrated into the Gleeble test chamber as shown in Figure 4.5. Four power cables were utilized to connect the IHTC-mate to the resistance heating system of Gleeble. Comprised of two blank holders, a die and punch, a sliding block and a rig frame, IHTC-mate is able to duplicate different warm and hot forming processes, and is especially capable of the ultra-fast heating through resistance heating. The sliding block on the frame where the blank holders were installed was made of acetal resin to

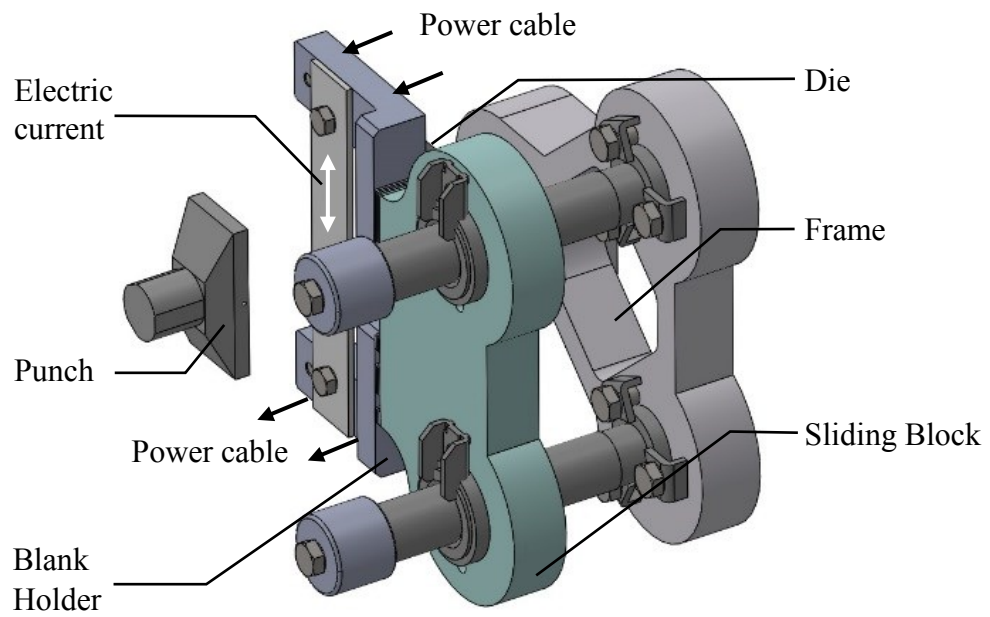


Fig 4.4 Design of IHTC-mate test rig

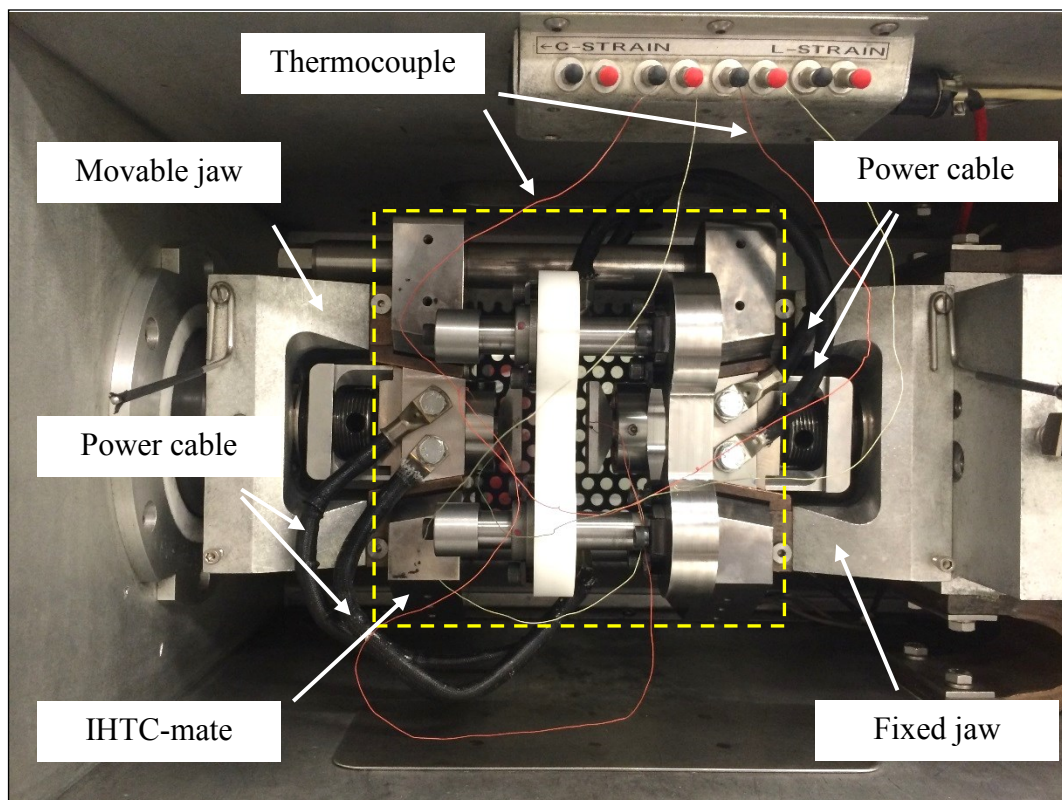


Fig 4.5 Assembly of IHTC-mate in the Gleeble test chamber

insulate the specimen and blank holders from the rest of the rig. In order to eliminate the influence of strain hardening due to the deformation of the specimen, the die and punch with flat surface were used in this study.

For each test, a rectangular specimen was fixed onto the blank holder and positioned between the punch and die. A thermocouple was embedded at the centre of the test specimen to realize the temperature measurement and feedback control. Two additional thermocouples were inserted into the punch and blank holders and connected to the data logger. The specimen was heated by direct resistance heating. The temperature evolution profile, forming speed and contact pressure in the form of the punch force were programmed in the control system in advance. The specimen was heated following the predefined temperature history. Once the target temperature was reached, the punch immediately moved towards the specimen, compressing against the die and holding with the pre-set die-closing force. When the specimen was quenched to the pre-set temperature, the punch moved to its initial position and the specimen was cooled in air. The samples were subsequently prepared for the hardness measurement.

4.2.4 100 Tonne ESH high-speed press and the gas spring cushion system

The ESH 100 tonne high-speed hydraulic press, on which the Uni-Form is installed is shown in Figure 4.6. The usable stroke of this press is up to 100 mm and the maximum ram speed is 600 mm/s. This press was initially controlled by a control cabinet, which used the analogue signal control. The control system of Uni-Form was initially designed in line with the analogue control. Soon after, the control cabinet was converted into a digital control system as shown in Figure 3.13 and the control system of Uni-Form was redesigned for compatibility.

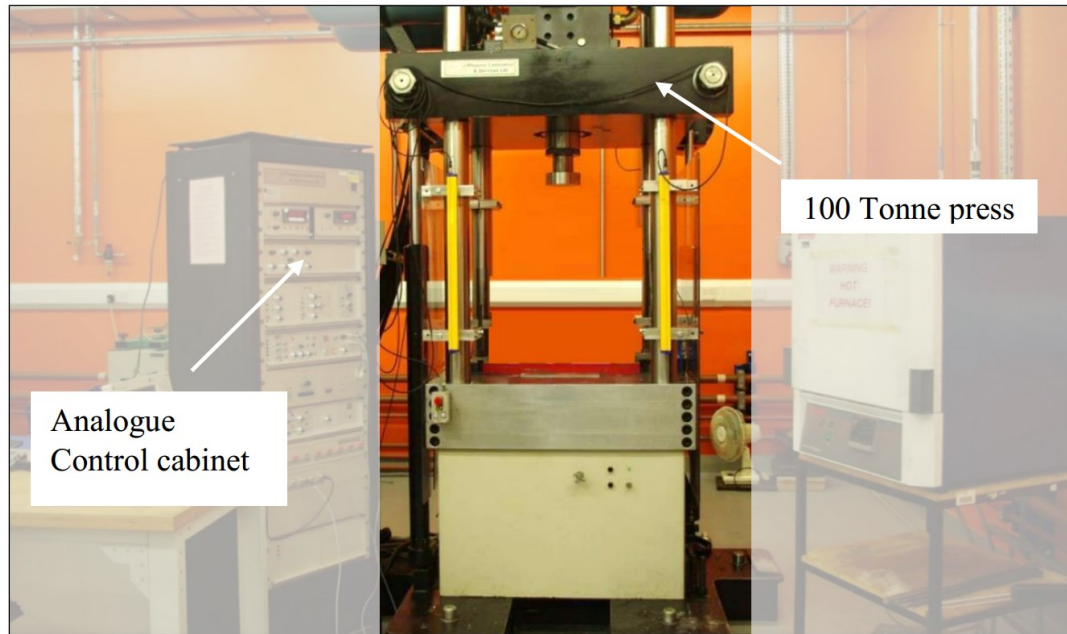


Fig. 4.6 100 Tonne ESH high-speed press with analogue control cabinet

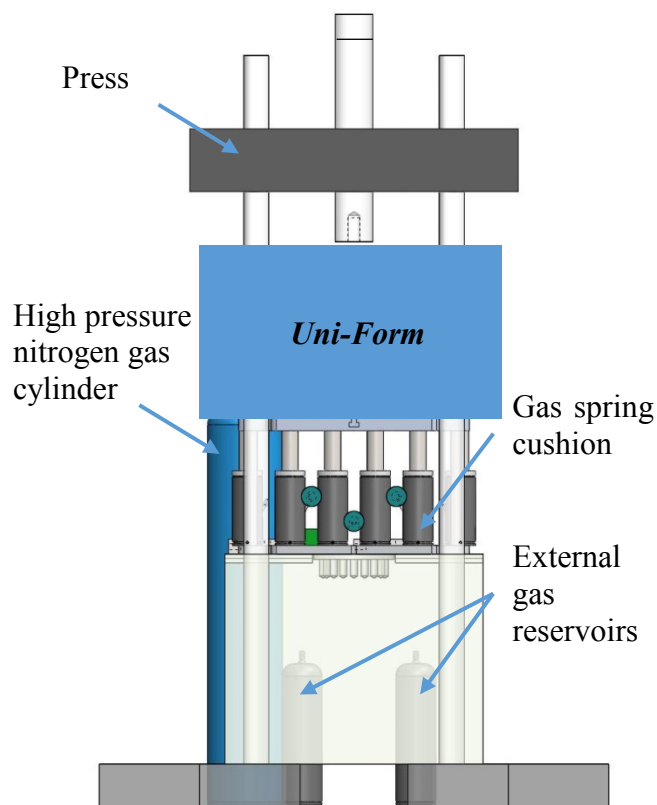


Fig 4.7 The layout of the gas spring cushion installed on the press (side view)

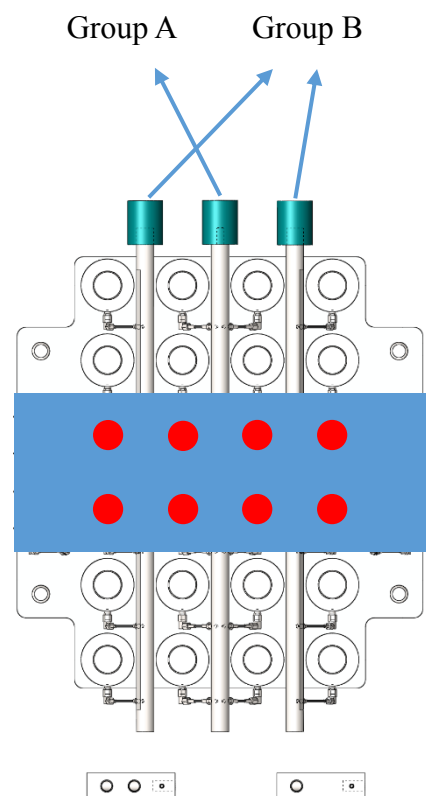


Fig 4.8 The layout of the individual gas spring in the cushion system (top view)

As shown in Section 3.3.2, a gas-spring cushion system was employed for Uni-Form, which was invented by the author's research group (Wang, 2012). The detailed design of this cushion system is presented in Figure 4.7 and 4.8. The system is designed to provide variable supporting force for the experimental apparatus positioned above it. A total of 28 gas springs (Design-Tite® RL5000×100) divided into two groups (Group A and Group B in Figure 4.8) are contained in this cushion system. A high pressure nitrogen gas cylinder is utilized to charge the gas springs. Two external gas reservoirs are connected to these two groups respectively in order to maintain the gas spring pressure and supporting force constant during the test. In this study, the gas springs were charged to 20 bar to ensure the sufficient platen heaters pressure and the die closing pressure. As shown in Figure 3.10, the middle plate of Uni-Form was supported by eight pillars connecting the central eight gas springs, which are high-lighted by red colour in Figure 4.8. As such, the rest of the gas springs provide the support for Uni-Form. The detailed calculations of the relationship between the pressure of the gas spring cushion and the supporting forces within Uni-Form can be found in Appendix 1 (e).

4.3 Test scheme of the FAST process study

4.3.1 Precipitation hardening behaviour of AA6082

The precipitation hardening behaviour of aluminium alloy AA6082 under various ageing conditions was studied. The rectangular shaped specimens with dimensions of 120 x 20 x 1.5 mm were laser cut from the as-delivered blanks. According to the previous experiments (Luan et al., 2016 (a)) and literature (Mohamed and Samuel, 2012), the solutionizing temperature (T_{SHT}) of the AA6082 was approximately 525°C and with a soaking time (t_{SHT}) of 0.5 hours.

To heat the specimens, a chamber furnace (Lenton ECF 12/45) was heated in advance, and a pair of iron blocks (160 x 120 x 20 mm) were positioned in the chamber as shown in Figure 4.9 to act as thermal reservoirs. Once the temperature of the furnace and the iron blocks reached the target temperature and was maintained for 2 hours, the specimens were then placed in between the two iron blocks, eliminating the temperature fluctuation during the heat treatment. This procedure was standardized for all the solution heat treatment and artificial ageing tests in this study.

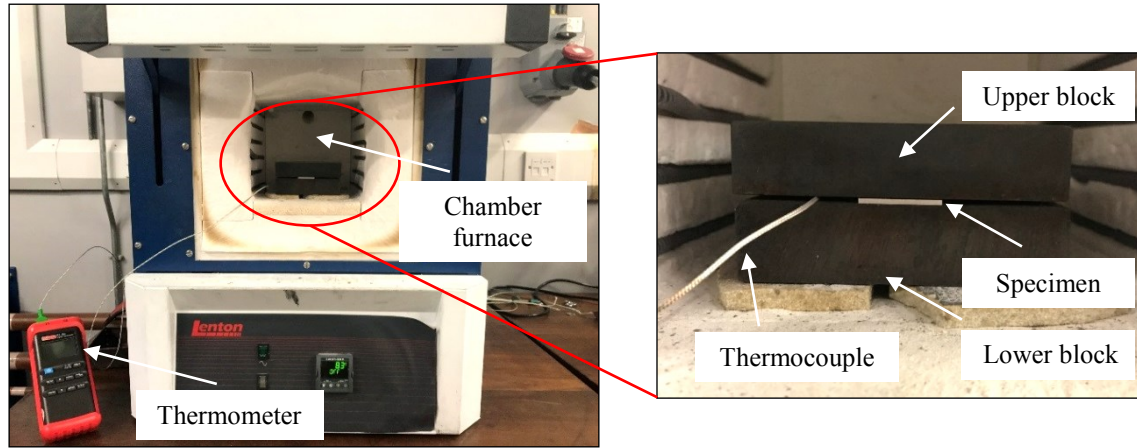


Fig 4.9 Equipment used to conduct the solution heat treatment and the artificial ageing treatment tests

For the natural ageing test, the heat treatment temperature profile is shown in Figure 4.10. Since the as-delivered blank was in T6 temper (fully artificially aged), the specimens were first solution heat treated and quenched in cold water. The measurement on hardness was taken immediately after quenching and the samples were further stored at room temperature (T_{RT}). The evolution of hardness during natural ageing was measured every 12 hours ($t_0, t_1 \dots t_n$) during the first week and was further tested every week during the material's shelf life of 6 months and no change was found. The specimen was regarded as T4 temper (naturally aged) when its hardness remained constant during the storage and would be utilized in the following studies of FAST.

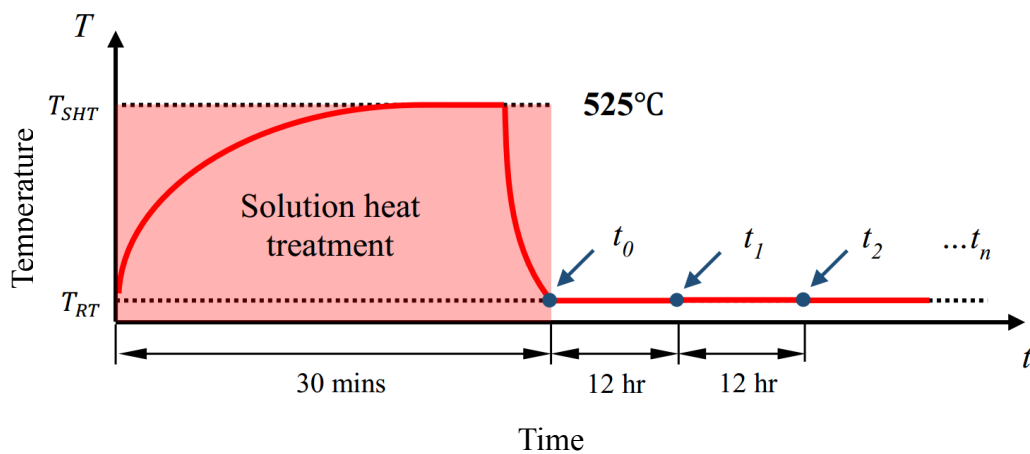


Fig 4.10 Schematic temperature profile of the natural ageing test

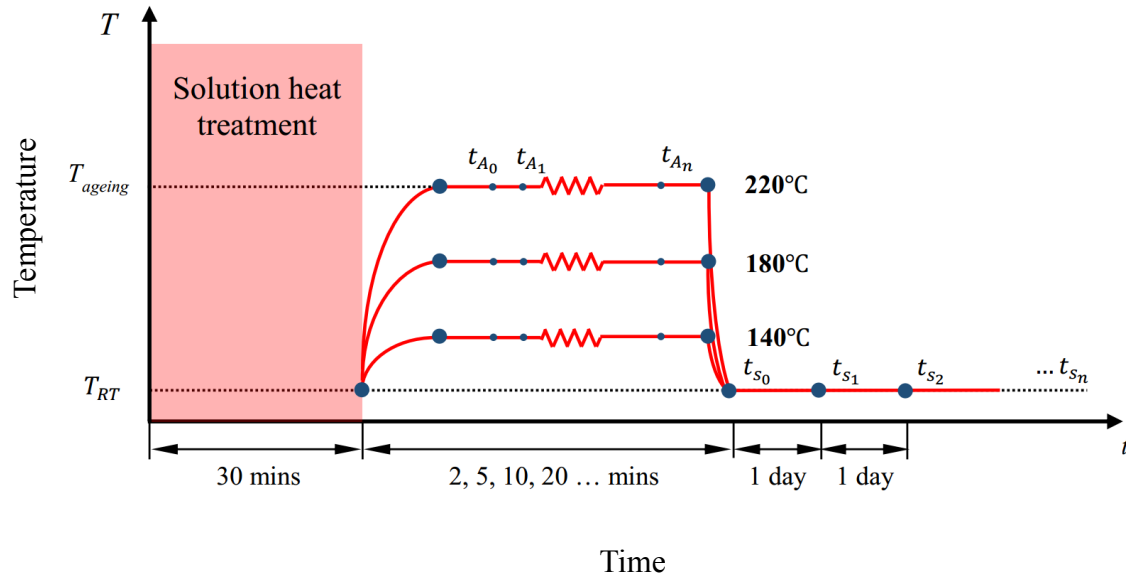


Fig 4.11 Schematic temperature profiles of the artificial ageing tests with additional room temperature storage

For the artificial ageing tests, three different ageing temperatures (T_{ageing}), namely 140°C , 180°C and 220°C were selected in this study, according to the literature review on the artificial ageing of 6xxx series aluminium alloys (Masuda et al., 2010; Birol, 2005 (a), Birol, 2005 (c); Esmaeili et al., 2003 (c)). The heat treatment temperature profile can be seen in Figure 4.11. The samples for each ageing temperature were taken from the furnace at 2 minutes, 5 minutes and at a time intervals of 10 minutes thereafter ($t_{A_0}, t_{A_1} \dots t_{A_n}$), quenched in cold water and polished for hardness measurement.

The influence of natural ageing was found still evident at some artificial ageing conditions, such as 140°C/2 min, 140°C/5 min and 180°C/2 min. Thus, the hardness evolution during the subsequent room temperature storage was monitored daily ($t_{s_0}, t_{s_1} \dots t_{s_n}$) for 7 days. The test matrix of the artificial ageing and room temperature (RT) storage study is shown in Table 4.2. At least three tests were conducted for each test condition to ensure repeatability.

Table 4.2 Test matrix of the artificial ageing and room temperature storage study

Time (minutes) Temperature(°C)	Artificial Ageing Time (t_{A_n})						
	2	5	10	20	30	40	50
140	✓	✓	✓	✓	✓	✓	✓
180	✓	✓	✓	✓	✓	✓	✓
220	✓	✓	✓	✓	✓	✓	✓

Time (days) Temperature	Storage Time (t_{s_n})						
	0	1	2	3	4	5	6
RT	✓	✓	✓	✓	✓	✓	✓

4.3.2 Heat treatment test

The specimens obtained from the natural ageing study were in T4 temper. The T4 and as-delivered T6 temper samples were heat treated following the FAST process in order to provide the proof-of-concept, explore the performance and study the mechanism of FAST distinguished from other sheet forming technologies for aluminium alloys.

All the heat treatment studies were conducted using the dedicated test facility IHTC-mate, following the procedure demonstrated in Section 4.2.3. The rectangular samples were drilled with two holes at the ends in order to be assembled on the IHTC-mate. The design of the sample is shown in Figure 4.12.

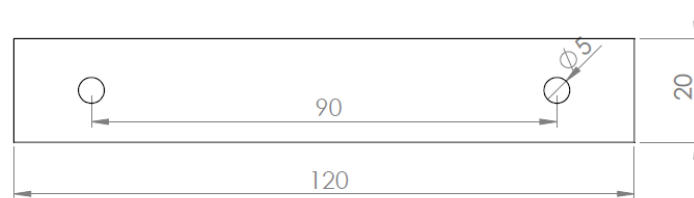


Fig 4.12 The geometry of specimens used in the heat treatment tests (Dimension in mm)

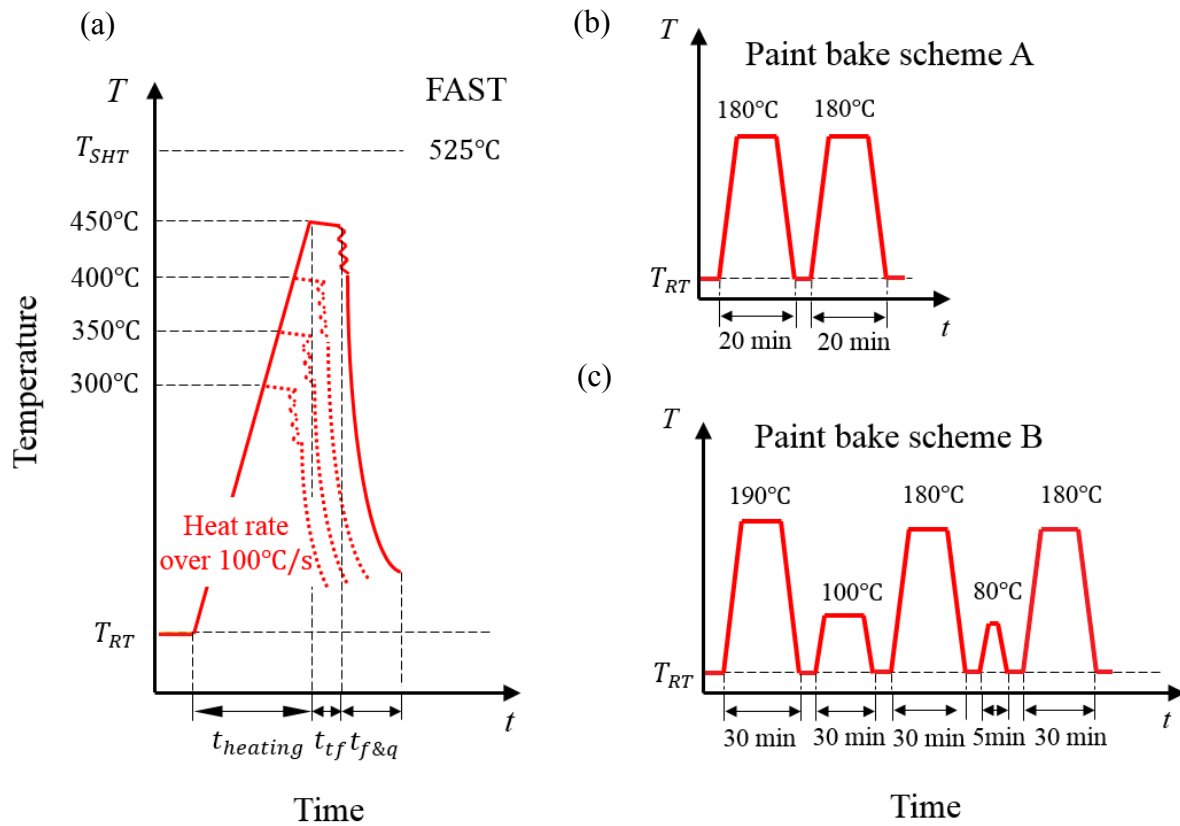


Fig 4.13 Schematic temperature profile of (a) the heat treatment tests of FAST, (b) Paint bake scheme A (P&B A) and (c) Paint bake scheme B (P&B B)

The temperature profile of the FAST heat treatment tests is shown in Figure 4.13 (a). $t_{heating}$ accounts for the blank heating time, t_{tf} is the blank transfer time and $t_{f\&q}$ refers to the blank forming and in-die quenching time. The target temperature ranged from 300°C to 450°C at a temperature interval of 50°C and the heating rate was greater than 100°C/s. As shown in Section 3.2.2 and 3.2.3, the paint bake cycles of automakers are purposed to be integrated into the FAST process in order to verify the performance of FAST under industrial production scenarios. Therefore, once the FAST process was completed, the two sets of paint bake cycles were applied to the specimens respectively, as shown in Figure 4.13 (b) and (c). The evolution of hardness during the test were measured at each stage namely before the FAST process, after the FAST process and after the paint bake cycles.

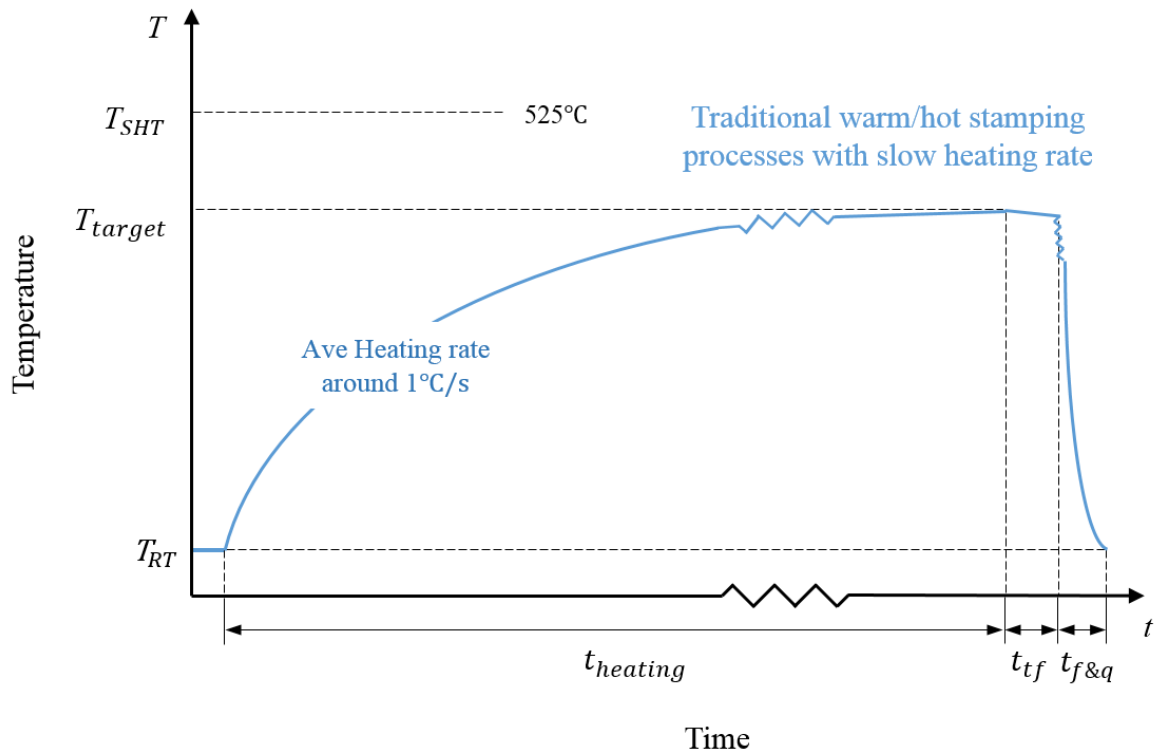


Fig 4.14 Schematic temperature profile of warm/hot stamping processes at a slow heating rate of 1°C/s

In addition, the heat treatment tests following the traditional warm and hot stamping processes with a slow heating rate were conducted on the IHTC-mate using the T4 and T6 temper specimens. In warm and hot stamping processes, the specimens are generally heated in a chamber furnace or by heated forming tools under a slow heating rate. The difference on the temperature evolution between FAST and traditional hot and warm stamping processes can be found in Figure 4.13 (a) and Figure 4.14. The heating rates of the chamber furnaces with different geometries were measured under different furnace temperatures in the author's laboratory. The experimental data on heating rate is presented in Appendix 1 (f). It was found that the average heating rate using the chamber furnace to heat the aluminium blank with a thickness of 1.5 mm was approximately 1°C/s , which was in accordance with the warm forming process currently used by vehicle manufacturers (Harrison et al., 2013 (a)).

The temperature history was programed in Gleeble and the same target temperatures, namely 300°C , 350°C , 400°C and 450°C , as the FAST processes were applied. All these samples were

further heat treated using the two paint bake cycles described in Figure 4.13 (b) and (c) respectively and the hardness measurements were taken at each stage during the test.

4.3.3 Strength analysis of the FAST formed components

The strength analysis of the FAST formed components were conducted through the measurement of hardness at different forming stages and the microstructure analysis of specimens at specific forming stages of the FAST process using transmission electron microscopy (TEM).

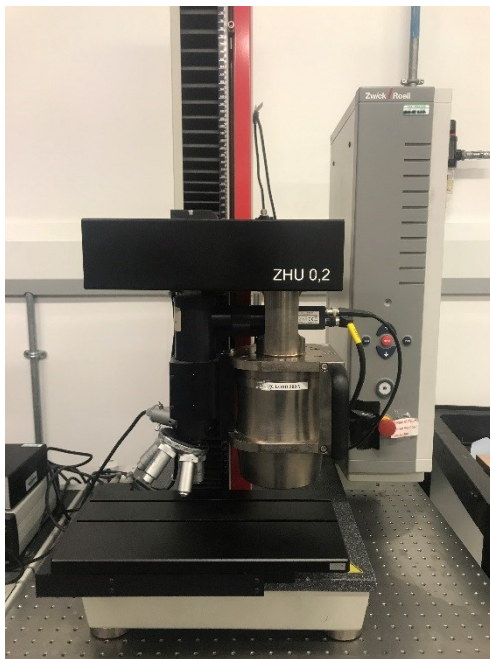


Fig. 4.15 Zwick/Roell Z2.5 universal hardness tester

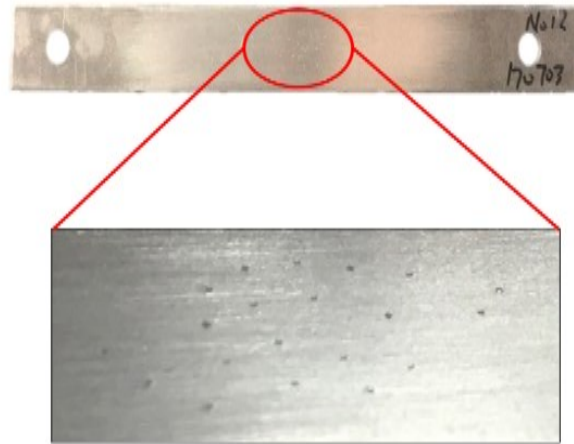


Fig 4.16 Hardness measurement of the polished sample

A Zwick/Roell Z2.5 universal hardness tester was used for the hardness measurement, as can be seen in Figure 4.15. A load of 50N (HV5) and dwell time of 10 seconds were assigned for the measurement. The specimens after each stage of the heat treatment test were polished using sandpaper to ensure the borders and corners of the indentation were clearly visible. Grit 800 (P800) and Grit 1200 (P1200) sandpapers were used successively to achieve a “super fine (ISO, 2013)” surface finish. For each measurement, five indentations were performed to obtain the average hardness, as shown in Figure 4.16.

Transmission electron microscopy (TEM) scans were performed on the specimens after the FAST process. A FEI Technai F20S/TEM system was employed in this study. The preparation of the TEM samples followed a standard processing route (Sridhara Rao et al., 2010), in which the samples were mechanically thinned to $100\ \mu\text{m}$ followed by electropolishing. A disc-shape sample 3 mm in diameter was punched from the ground slice, and ion thinning was conducted by Gatan Precision Ion Polishing System Model 691. More than fifty images were taken in different scales of each sample and all the images were acquired along the $\langle 100 \rangle$ direction of the aluminium matrix.

4.3.4 Uniaxial tensile test under the ultra-fast heating conditions

The stress-strain characteristics of the specimens under the ultra-fast heating conditions were studied through the uniaxial tensile tests on Gleeble 3800 thermal-mechanical simulator. The dog-bone shaped specimens were designed following the standard test methods for tension testing of metallic materials (ASTM International, 2016) and the dimensional limitation of the Gleeble test chamber. The gauge length of the specimen, in which the uniform strain occur, was calibrated through the digital image correlation (DIC) technique (Liu et al., 2015) and determined as 40 mm. The geometry of the specimen is shown in Figure 4.17.

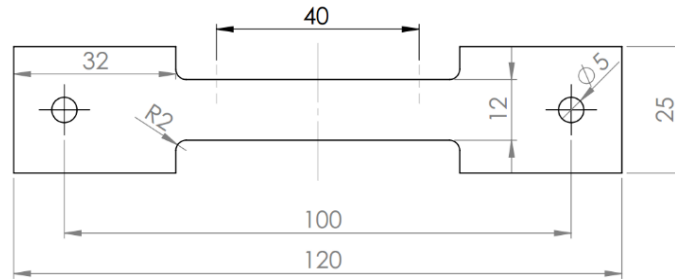


Fig 4.17 The geometry of specimens used in the uniaxial tensile tests (Dimension in mm)

Prior to each tensile test, the specimen is welded with a pair of Type-K thermocouples at the centre to measure the real-time temperature and provide feedback control. The specimen was clamped by two pairs of grips on the ends and fixed in the jaws of the Gleeble. The C-gauge was employed to measure the width change of the specimen. The layout of the tensile test using Gleeble is shown in Figure 4.18.

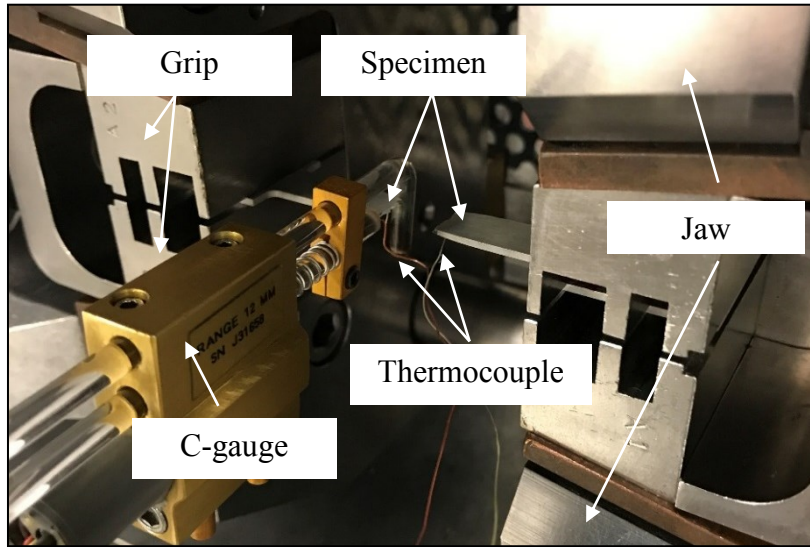


Fig 4.18 Layout of the uniaxial tensile test in Gleeble

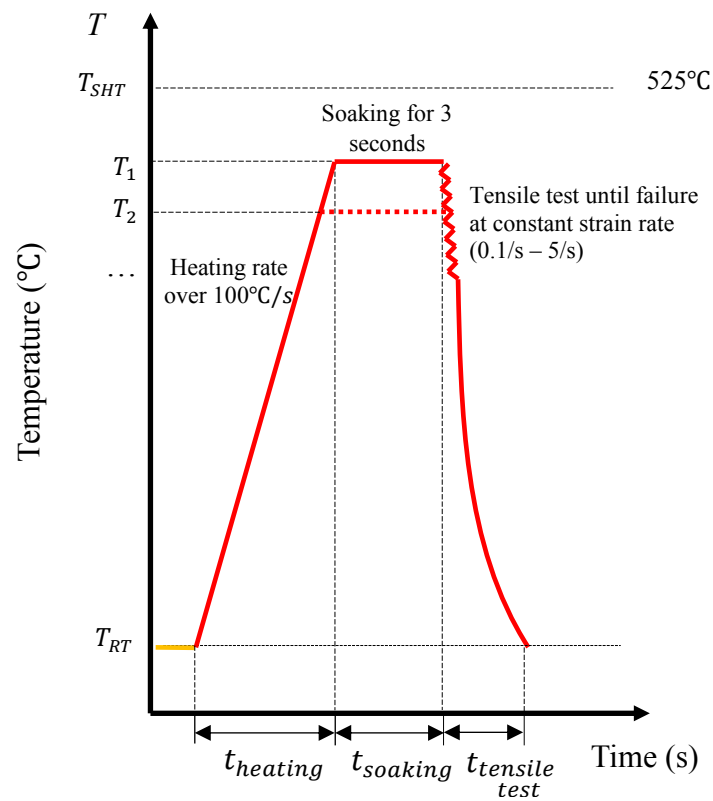


Fig. 4.19 Schematic temperature profile of uniaxial tensile test

The temperature profile of the uniaxial tensile test is shown in Figure 4.19. The specimen was heated up to the target temperature (T_1 , T_2 ...) under the ultra-fast heating rate greater than 100°C/s , soaked for 3 seconds duplicating the transferring process of FAST and then tensile

tested to failure. The target temperatures ranged from 300°C to 450°C with different strain rates from 0.1/s to 5/s representing the typical conditions encountered in the sheet metal forming process. The tests were also conducted at the room temperature (RT). The test matrix is shown in Table 4.3. At least three tests were conducted for each test condition to ensure repeatability.

Table 4.3 Test matrix of the uniaxial tensile test under ultra-fast heating conditions
(For AA6082 in T6 and T4 tempers)

Temperature (°C) Strain Rate $\dot{\epsilon}$ (1/s)	300	350	400	450	RT
0.1	✓			✓	
1	✓	✓	✓	✓	✓
5	✓			✓	

4.4 FAST forming trials via Uni-Form

4.4.1 Forming of the U-shape components

Uni-Form was used to conduct the FAST forming trials, as shown in Figure 4.20. For this work, U-shape forming tool was installed on the Uni-Form, which a typical geometry used in sheet metal forming testing (Wang et al., 2017; Black, 2013; Liu et al., 2002). Referring to the relevant international standards (British Standard, 2017 (b); ASTM International, 2012) and the geometry of test rig adopted by Jaguar Land Rover on springback studies, the design of the forming tools is shown in Figure 4.21 (Bhattacharya et al., 2011 (a); Stanton et al., 2009).

The specimen was designed as an H-shaped rectangular blank with four prongs for transferring through the conveyor system and minimizing the heat loss of the central section during the transfer compared with the normal rectangular shaped specimen. The dimensions of the rectangular section of the blank were $240 \times 86 \times 1.5$ mm. The design of the specimen can be found in Figure 4.22. The specimens were laser cut from the as-delivered blanks in T6 temper and heat treated into the T4 temper using the chamber furnace (Lenton 20-302112 special oven), as shown in Figure 4.23 (a).

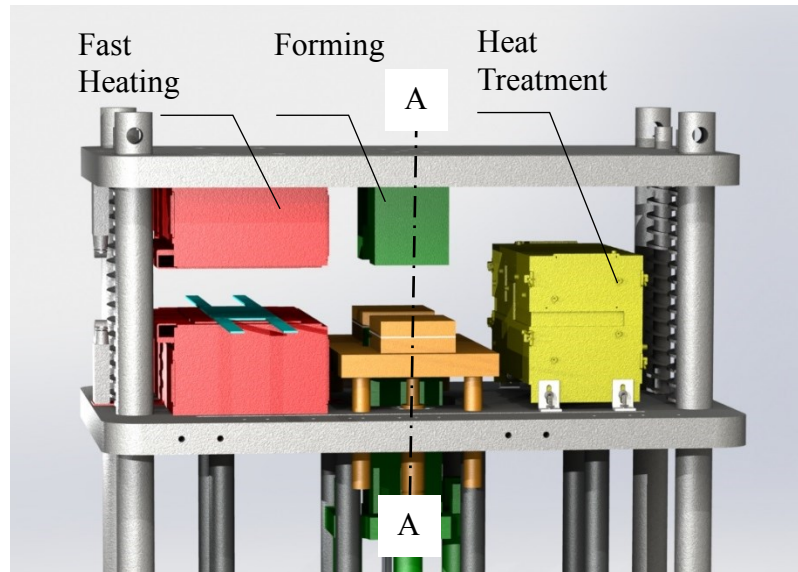


Fig 4.20 Layout of the forming trial test in Uni-Form

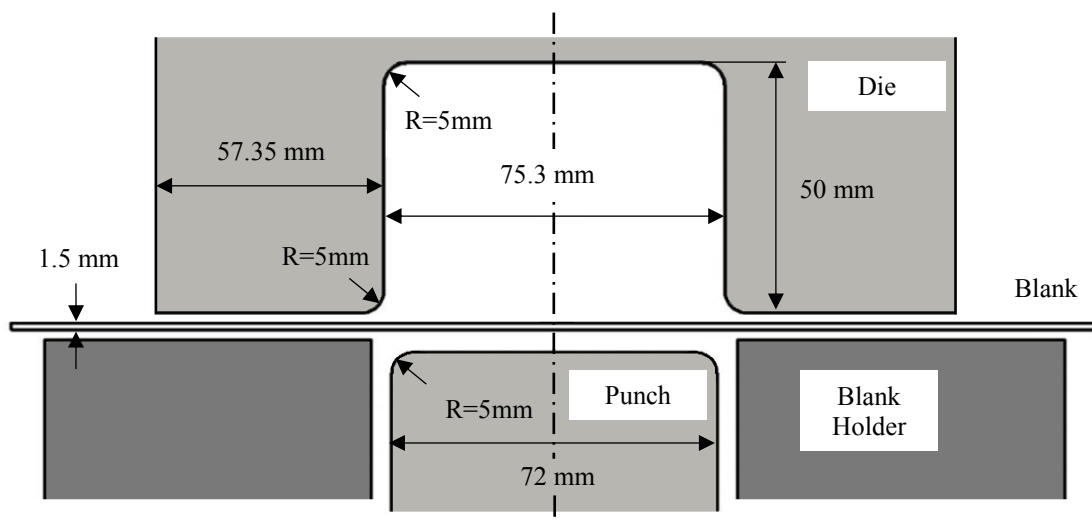


Fig 4.21 The geometry of the U-shape forming tools

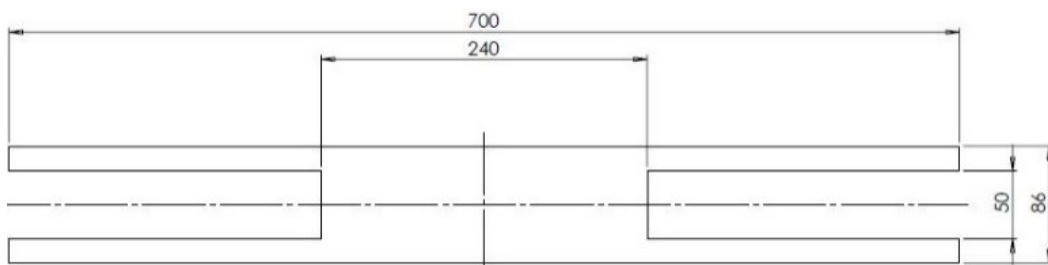


Fig 4.22 The geometry of specimens used in the forming trial tests
(Dimension in mm)

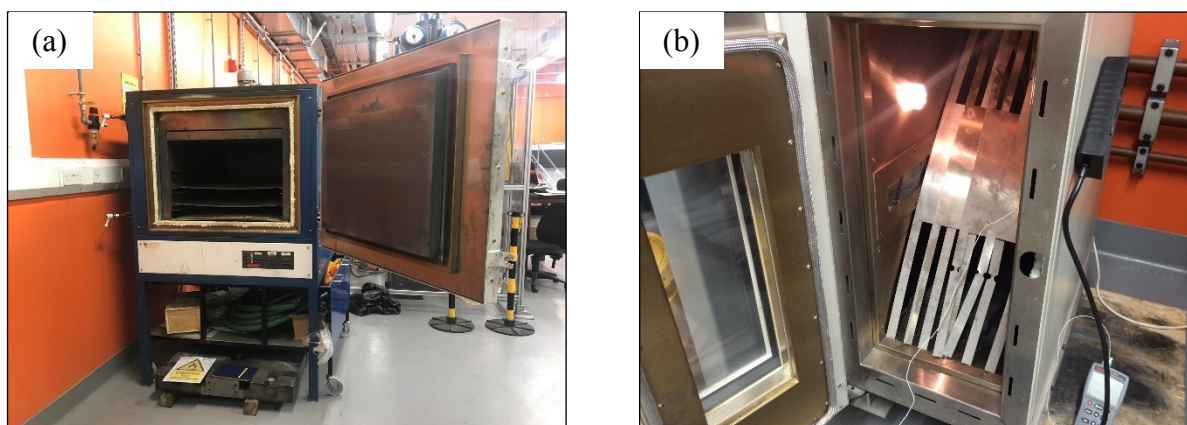


Fig 4.23 (a) Lenton 20-302112 special oven for solution heat treatment
(b) Instron EC/613 chamber furnace for paint bake scheme A

Prior to each test, the specimen was first placed on the designated position on the conveyor. Once the test began, the specimen was transferred to the platen heater, and was compressed and heated to the target temperature. Secondly, the press was released and the hot specimen was transferred to the forming tools. Finally, the U-shape component was formed and quenched to 180°C in the closed dies. The paint bake scheme A (P&B A) was conducted using the chamber furnace (Instron EC/613), as shown in Figure 4.23 (b) and the paint bake scheme B (P&B B) was carried out using the incubation chamber of Uni-Form. The properties of the formed components, such as springback, post-form strength and surface roughness were subsequently studied.

Table 4.4 Test matrix of the FAST forming trials

Temperature (°C) Speed (mm/s)	RT	300	350	400	450
100	√	√	√	√	√
150		√			
250		√			
380		√			

The effects of material temper, forming speed and forming temperature of the FAST process were explored. The forming temperature ranged from room temperature to 450°C and the forming speed varied from 100 mm/s to 380 mm/s. Table 4.4 demonstrates the test matrix of the forming trials and the formed components are presented in Appendix 3.

4.4.2 Benchmark study on cycle time

Cycle time is the fastest repeatable time in which one part can be produced during the manufacturing process (Roser, 2015). Specific to sheet metal forming processes, the cycle time accounts for the length of time transforming a metal blank to a formed component with the required mechanical properties. The cycle time consists of the pre-treatment of the metal blank, the heating time, transferring time, forming and quenching time, and the post-form processing time. Minimising the cycle time is highly desirable in the automotive industry, due to the tremendous potential savings on manufacturing cost and the increased production rate. There are also many other benefits of shorter cycle time, such as being able to diagnose problems in a forming process quicker, allowing for faster process correction and refinement (Roser, 2016).

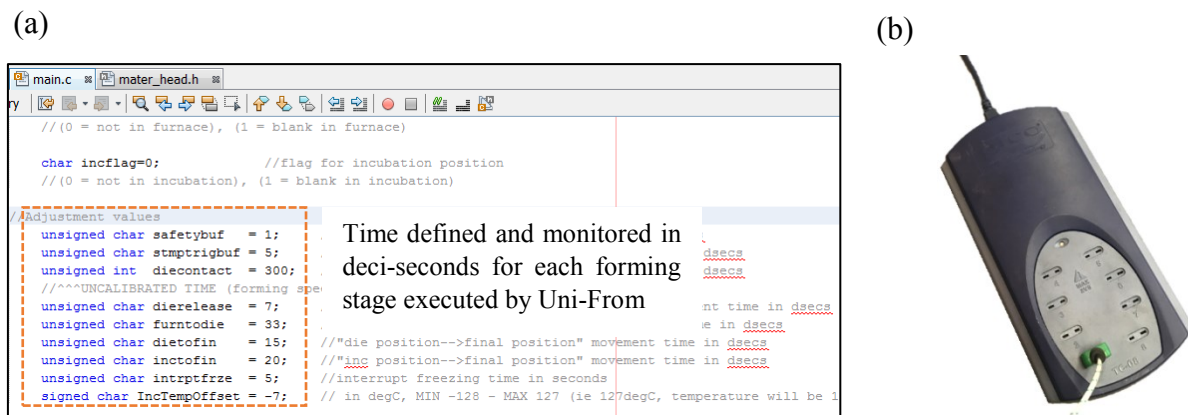


Fig 4.24 Cycle time measurement approaches: (a) computer program, (b) thermocouple and data logger (pico TC-08)

In this study, the FAST process at two different target temperatures, 300°C and 450°C, and three sheet metal forming processes for aluminium alloy, HFQ, W-Temper and cold stamping were conducted in the laboratory by producing an identical U-shape component to determine each

cycle time. The manufacturing cycle time for the warm forming process was obtained from the literature (Harrison et al., 2013 (a)).

Two approaches were utilized to record the cycle time, namely the computer program of the Uni-Form (*C*) and the thermocouple & data logger (*D*), as shown in Figure 4.24. The cycle time of the FAST forming trials was monitored and exported from the control program of Uni-Form in MPLAB X IDE in term of each forming stage. For other forming processes, the cycle times were obtained by calibrating the specimen's temperature evolution profile by the data logger (pico TC-08) during the forming process.

The cycle time of these six forming processes were recorded in terms of four main sections; the pre-processing time, the heating time, the forming time and the post-processing time. The measuring methods applied, corresponding to each stage of the different forming technologies, are summarized in Table 4.5, where *NA* represents not applicable and *L* represents data obtained from the literature.

Table 4.5 Cycle time measurement approaches for different forming technologies

Measuring Methods Cycle time Forming Tech.	Pre Proc. time	Heating time	Forming time	Post Proc. time
FAST (300°C)	<i>NA</i>	<i>C</i>	<i>C</i>	<i>NA</i>
FAST (450°C)	<i>NA</i>	<i>C</i>	<i>C</i>	<i>NA</i>
HFQ	<i>NA</i>	<i>D</i>	<i>D</i>	<i>D</i>
W-Temper	<i>D</i>	<i>NA</i>	<i>C</i>	<i>C</i>
Warm Forming	<i>NA</i>	<i>L</i>	<i>L</i>	<i>NA</i>
Cold forming	<i>NA</i>	<i>NA</i>	<i>D</i>	<i>NA</i>

4.5 Summary

In this chapter, a series of experiments centred on the FAST process for the aluminium alloy AA6082 have been designed and conducted. The precipitation hardening behaviour of AA6082 under different ageing temperatures and time were studied via natural ageing and artificial ageing tests. The proof-of-concept and the performance of FAST was investigated through the

heat treatment tests on the developed test facility IHTC-mate. The effects of heating rate, material temper, forming temperature and paint bake cycles were explored. Hardness measurement was applied in all tests to verify the strength of the specimens and evaluate the performance of FAST at each forming stage. TEM observation was also employed to the specimens after the FAST process, and would be correlated with the hardness measurement in the discussion of the mechanism of FAST in Chapter 5. In addition, the thermo-mechanical properties of AA6082-T4 and T6 under the ultra-fast heating conditions were studied through the uniaxial tensile tests on Gleeble. These tests enabled the influence of material temper, temperature and strain rate to be investigated. Through the forming trials on the dedicated pilot production line, the influence of forming temperature, forming speed and material temper on the mechanical properties of the formed components using FAST were studied. Moreover, the benchmark study on cycle time of FAST and other forming processes provided an insight into the key factors influencing the production efficiency.

Chapter 5

Results and discussion of the experimental investigation of FAST

5.1 Introduction

In this chapter, the detailed results of the experimental study outlined in the previous chapter are presented and discussed to characterise the FAST process for aluminium alloy AA6082 in a comprehensive way. The natural ageing and artificial ageing tests were performed to investigate the effects of artificial ageing temperature, artificial ageing time and ambient temperature storage on the precipitation hardening behaviour of AA6082. Moreover, the mechanisms of FAST were investigated through the heat treatment tests and the strength analysis of the FAST processed AA6082-T4 and T6 specimens. Transmission Electron Microscopy (TEM) scans were employed and correlated with the strength analysis to gain an in-depth understanding of the microstructural mechanisms. In addition, uniaxial tensile tests were conducted to illustrate the thermo-mechanical properties of AA6082 in different tempers under the ultra-fast heating conditions.

5.2 Precipitation hardening behaviour of AA6082 under different ageing conditions

5.2.1 Natural ageing of AA6082

Figure 5.1 presents the natural ageing curve of aluminium alloy AA6082-T6 solution heat treated at 525°C for 30 minutes, water quenched and stored at room temperature. It is clear that the hardness of the material increased from 48 Hv and exhibited a quick rise to 74 Hv during the first day. The hardness continued to increase although at a lower rate to around 80 Hv on the fifth day, after which the hardness began to stabilise. The sample was further stored for 6

Chapter 5 is based on the co-authored paper work, Zhang & Luan et al., 2019, Development of the post-form strength prediction model for a high-strength 6xxx aluminium alloy with pre-existing precipitates and residual dislocations, International Journal of Plasticity, 119, 230-248 (Zhang, Luan et al., 2019)

months and the evolution of hardness during natural ageing was tested at a time interval of 7 days. As shown in Figure 5.2, the hardness of the naturally aged sample remained stable at approximately 80 Hv during storage. The results including the peak hardness and the general trend in hardness variation correspond to other research on natural ageing of other 6xxx series aluminium alloys (Yin et al., 2016).

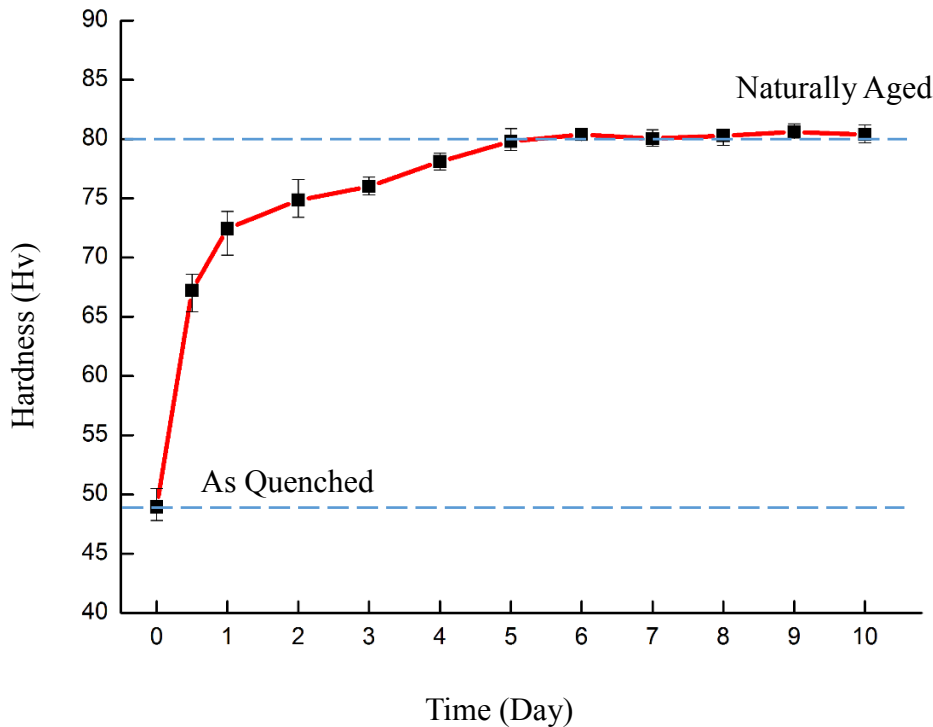


Fig 5.1 The natural ageing curve of aluminium alloy AA6082-T6 solution heat treated at 525°C for 30 minutes, water quenched and stored in open air

The AA6082-T6 after solution heat treatment and water quenching is at the supersaturated solid solution (SSSS) condition, where all the particles within the microstructure have been dissolved into the aluminium matrix. As a result, the hardness of the material reaches its minimum value of approximately 48 Hv. In general, the increase of hardness during room temperature storage occurs by the generation and growth of clusters (the so-called natural ageing clusters) with high number density, which has larger resistance to dislocation shearing compared with the supersaturated aluminium matrix.

As shown in Figure 5.1, the hardness initially increases rapidly followed by a decreasing growth rate and an eventual plateau. This behaviour can be explained by the decrease of the natural

ageing cluster growth rate during storage. Immediately after the solution heat treatment and quenching, the solute atoms are randomly distributed in the solid solution in the aluminium matrix. The high vacancy concentration facilitates the formation of clusters, which interact with dislocations and increase the strength of the material. As the natural ageing proceeds, the number of solutes in solid solution and the vacancies decrease and the solute–dislocation interactions become weaker (Cuniberti et al., 2010). Meanwhile, the ambient temperature cannot provide sufficient activation energy for the formation of other hardening phases during storage. As a result, the strength of the material plateaus after 5 days. The clustering is also reflected by the variation of the material electrical conductivity. As reported in the study by Birol (2005 (a)), the conductivity of naturally aged AA6016 was found to decrease quickly in the first 10 hours and then slowly during the following 10 days.

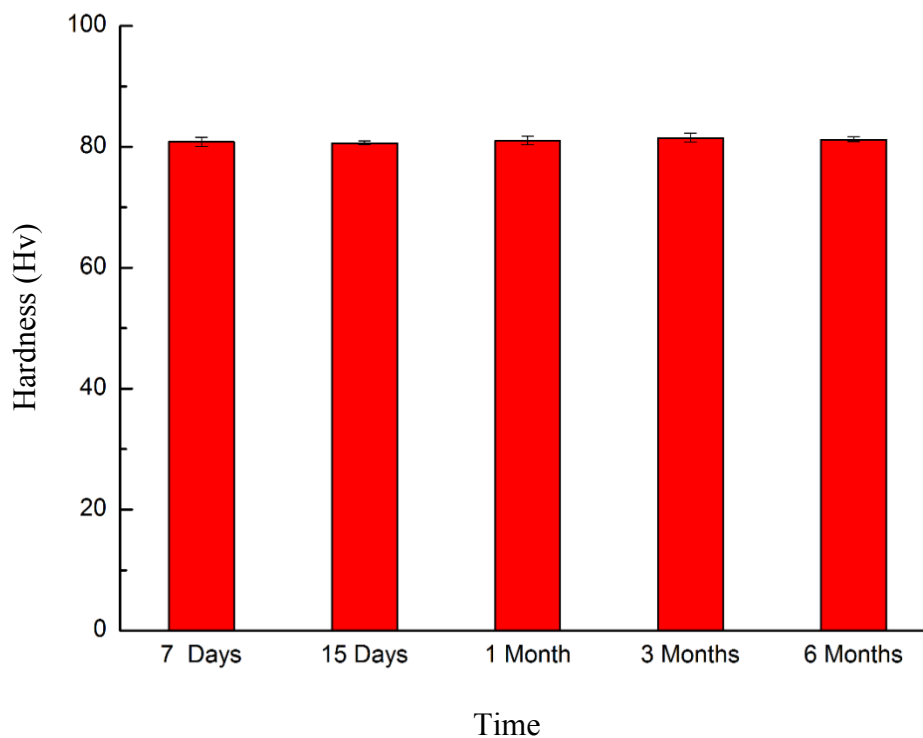


Fig 5.2 The effect of room temperature storage of the naturally aged samples

In addition, some studies suggested that the shear resistance of the natural ageing cluster may change during the natural ageing process due to the alteration of its composition, which results in the change of the hardening rate (Banhart et al., 2010). As reported by Gupta and Lloyd (1999), the formation of clusters is initially dominated by the silicon considering its higher

diffusivity and lower solubility followed by the formation of magnesium cluster and Si-Mg cluster. The natural ageing clusters could only be visualized by the three-dimensional atom probe (3DAP) due to the tiny geometry of these particles and the weak scattering contrast (Banhart et al., 2011). Therefore, the subtle changes of the quenched samples during room temperature storage is still not fully understood.

5.2.2 Artificial ageing of AA6082

The artificial ageing tests of the AA6082 were conducted at 140 °C, 180 °C and 220 °C respectively. The temperature range was selected based on the previous artificial ageing studies of 6xxx series aluminium alloys (Polat et al., 2015; Ozturk et al., 2010; Ismail et al., 1992) and the fact that a temperature of 180°C has been widely recognized as the optimum artificial ageing temperature for the alloy (Mukhopadhyay et al., 2012).

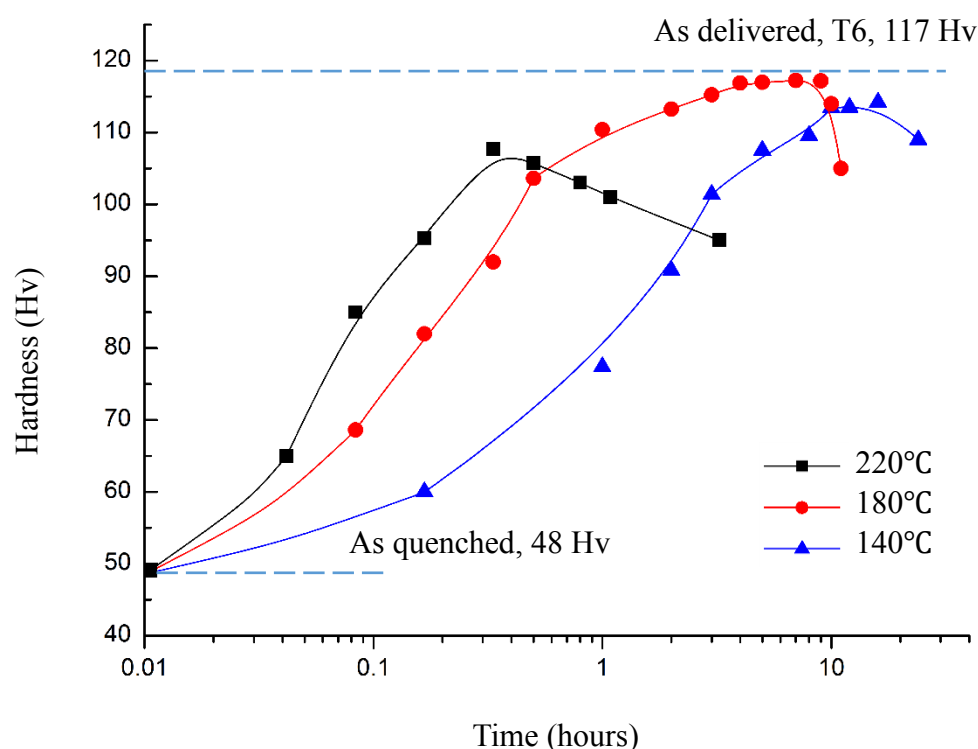


Fig 5.3 Isothermal artificial ageing curves of AA6082-T6 solution heat treated at 525°C for 30 minutes, water quenched and aged at different temperatures at 140°C, 180°C and 220°C

The artificial ageing curves for different ageing temperatures are presented in Figure 5.3, in which the time is presented logarithmically. It is noticed that the solutionized samples in all three artificial ageing conditions witnessed a fast increase of hardness in the early ageing stage, where the trend was similar to that of natural ageing. By the prolonged ageing time, the hardness of the samples continued to increase but at a much lower rate, reached the peak value before beginning to decrease with time. The hardness of the as-delivered AA6082-T6 material (117 Hv) and as-quenched condition (48 Hv) are highlighted by the blue dash line in Figure 5.3 as reference. The increased artificial ageing temperature facilitated the material to reach the peak hardness in a shorter time. When the artificial ageing temperature was 220°C, it took just 20 minutes to reach the peak hardness, while, it took 9 hours and 15 hours for the 180°C and 140°C ageing conditions respectively. However, the high artificial ageing temperature led to a lower peak hardness and earlier overageing. The peak hardness of the 220°C condition was 107 Hv compared to the peak hardness of 114 Hv at 140°C and 117 Hv when aged at 180°C.

In general, the variation of hardness with artificial ageing temperatures and time is attributed to the vacancy assisted diffusion mechanism and the different precipitates formed during the artificial ageing process. The initial fast increase in hardness for all three artificial ageing temperatures is due to the high rate of the formation of clusters and/or precipitates facilitated by the high concentration of the quenched-in vacancies. Meanwhile, it has been proved that both diffusion process and precipitation process are faster at higher temperature rather than those at lower temperature (Polat et al., 2015; Ninive et al., 2014), which contributes to the rapid growth in hardness when the artificial ageing temperature is 220°C. Accompanied by the successive formation of GP zones, coherent precipitates of the metastable phases β'' and β' were formed as the artificial ageing proceeded. The hardness continued to increase and the peak hardness corresponded to the optimized size and volume fraction of such precipitates, as reviewed in Section 2.2.2. The vacancies rapidly diminished and eventually became eliminated from the aluminium matrix during the ageing process, which resulted in the reduction of the precipitation hardening rate for all three conditions. Beyond the peak value, the hardness began to subsequently fall, which indicated the overageing. This is due to the increased size of the finely distributed precipitates and enlarged grain size, which make the dislocation bowing occur easier with fewer obstacles to confine the dislocation movement.

Following the artificial ageing tests, the aged samples were stored in open air for 7 days to explore the pre-ageing treatment effects on the stabilization of the mechanical properties of the aluminium alloy AA6082 during natural ageing. The hardness variations of the samples aged at three different temperatures are shown in Figure 5.4, Figure 5.5 and Figure 5.6 respectively. It is clear that when the artificial ageing was conducted at 180 °C and 220 °C the natural ageing effects had been largely suppressed, reflected in the stable hardness of almost all aged samples during the subsequent one week room temperature storage. While, for the sample artificially aged at 180°C and 220°C for 2 minutes, the hardness increased from 60.4 Hv to 68.3 Hv and from 65.0 Hv to 73.3 Hv after one week storage. The natural ageing effects were still present for samples aged at 140°C, especially for those artificial aged less than 30 minutes. The results imply that the prior artificial ageing at 180°C and 220°C are able to suppress the subsequent natural ageing and the hardness increase of the material. Similar results were also obtained for AA6061, AA6111 and AA6016 (Zhong et al., 2017 (a)). It was suggested that the diminishing of the vacancies in the microstructure is suppressed or delayed by the prior artificial ageing and reduces the effect of the natural ageing during storage (Zhong et al., 2017 (b)).

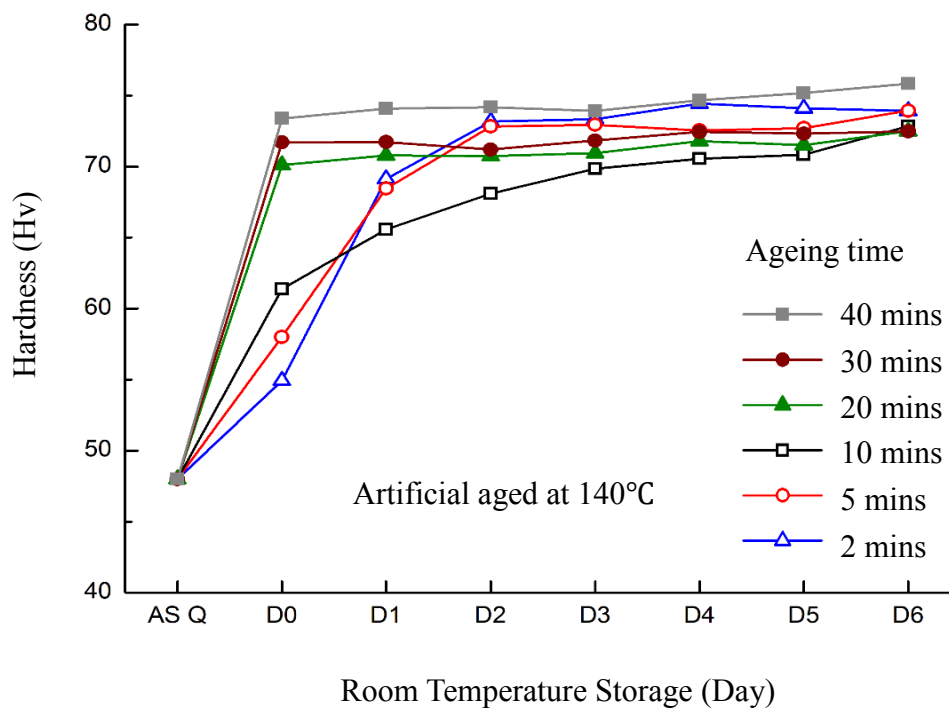


Fig 5.4 Influence of the room temperature storage time on the hardness of AA6082-T6 (solution heat treated and artificially aged at 140°C)

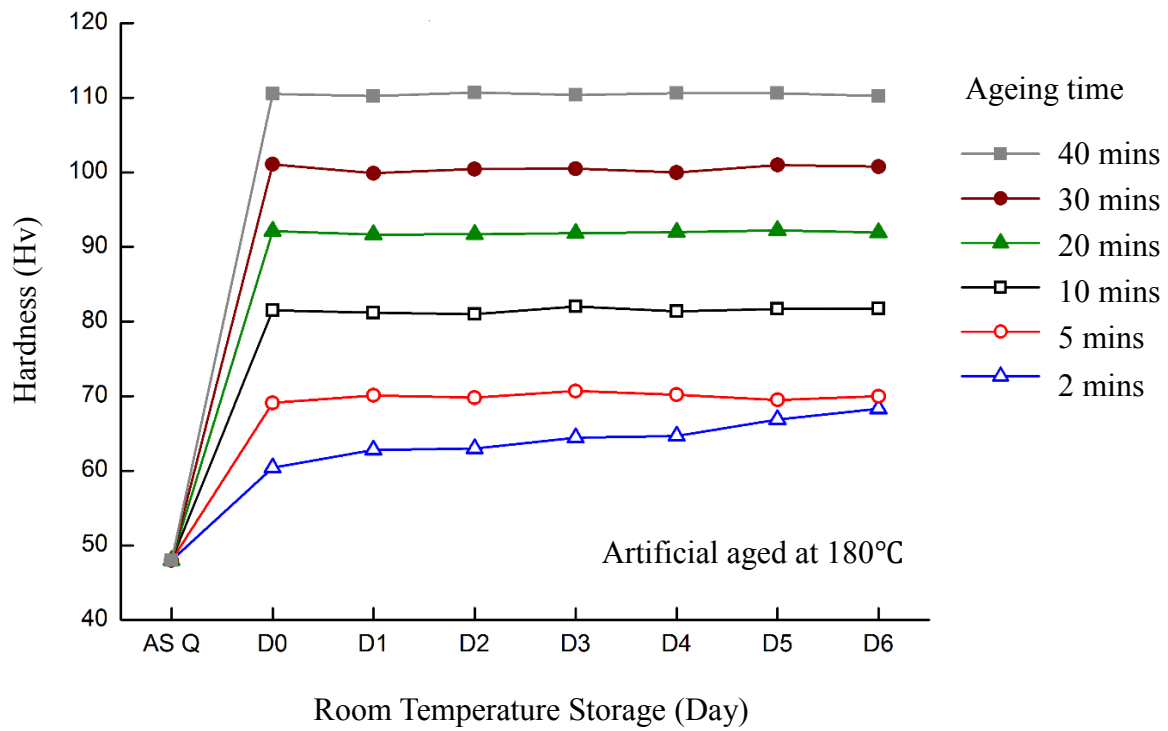


Fig 5.5 Influence of the room temperature storage time on the hardness of AA6082-T6 (solution heat treated and artificially aged at 180°C)

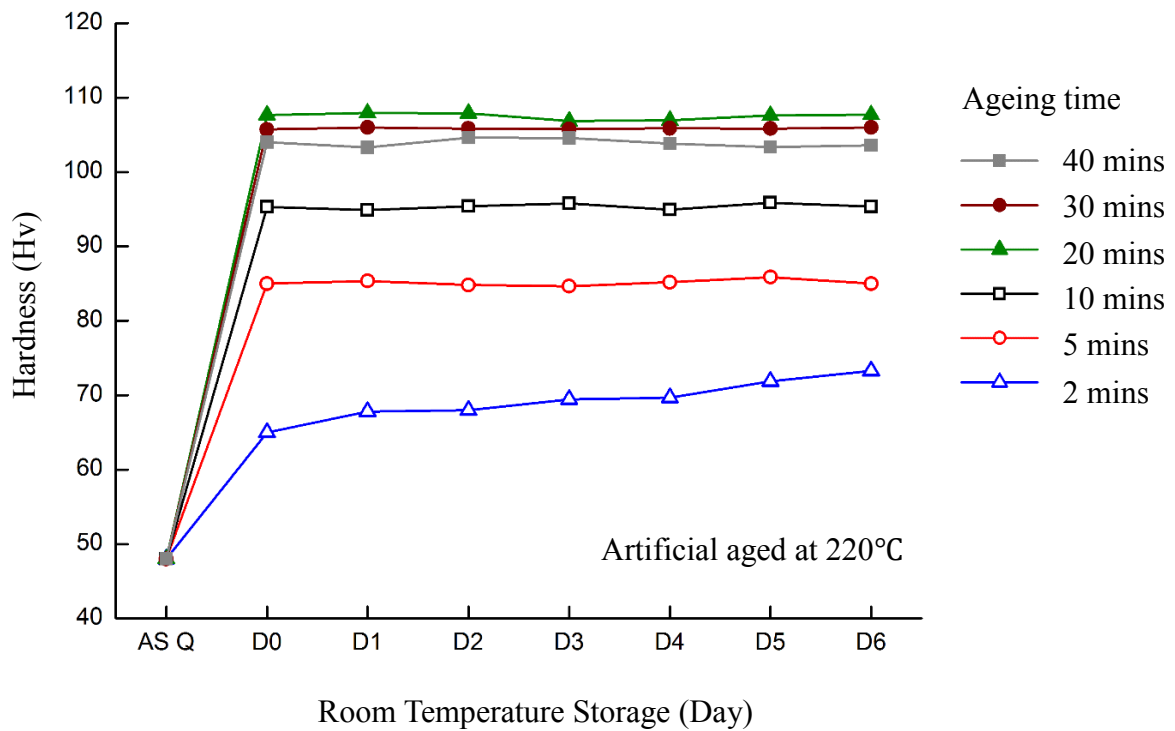


Fig 5.6 Influence of the room temperature storage time on the hardness of AA6082-T6 (solution heat treated and artificially aged at 220°C)

5.3 Mechanism study of FAST: heat treatment test and strength analysis

5.3.1 Effects of forming temperature on the microstructure evolutions of T4 tempered 6082 aluminium alloy during the FAST process

The heat treatment tests following the FAST process were conducted using the T4 tempered 6082 aluminium alloy at different target temperatures. Figure 5.7 shows the hardness evolution from the initial hardness, to the hardness attained after the FAST process (FAST) at two different target temperatures of 300°C and 450°C, and finally the hardness following the application of paint bake scheme A (P&B A) and paint bake scheme B (P&B B) respectively. When the FAST process was conducted at 300°C, the hardness of the T4 specimens reduced from 80.5 Hv to 52.8 Hv. A strength of over 105 Hv was achieved using either paint bake cycles, with no additional heat treatments required. When the FAST process was conducted at 450°C, the hardness of the T4 specimens decreased to approximately 48 Hv, and could be regained subsequently through either paint bake schemes. The paint bake response (PBR) of the material was as high as 66 Hv. Two more tests on the T4 specimens were conducted at 350°C and 400°C, as shown in Figure 5.8. A similar trend could be found for these two conditions, a post-form strength of over 110 Hv can be achieved using the paint bake cycles. For the T4 tempered specimens at all FAST process conditions, a strength level of over 95% of the material at the peak aged condition could be obtained using paint bake scheme B, and more than 90% could be obtained using paint bake scheme A.

The microstructure of naturally aged Al-Mg-Si alloys mainly consists of natural ageing clusters. The supersaturated solid solution (SSSS) condition of the aluminium matrix obtained by solution heat treatment and water quenching is fully altered by the formation of natural ageing clusters during the room temperature storage, with both quenched-in vacancies and solute atoms largely consumed in this process. This results in a degeneration of the paint bake and ageing responses of the material when it is directly subject to the artificial ageing after stamping (Yan et al., 2016; Abouarkoub et al., 2015; Marceau et al., 2013). According to the DSC study of AA6111 after solution heat treatment and quenching and at naturally aged conditions, a remarkable endothermic trough which corresponds to the dissolution of the natural ageing cluster could be observed before the exothermic peak relating to the formation of β'' (Birol, 2005 (a)). This reveals the delay of the age hardening process of the naturally aged samples

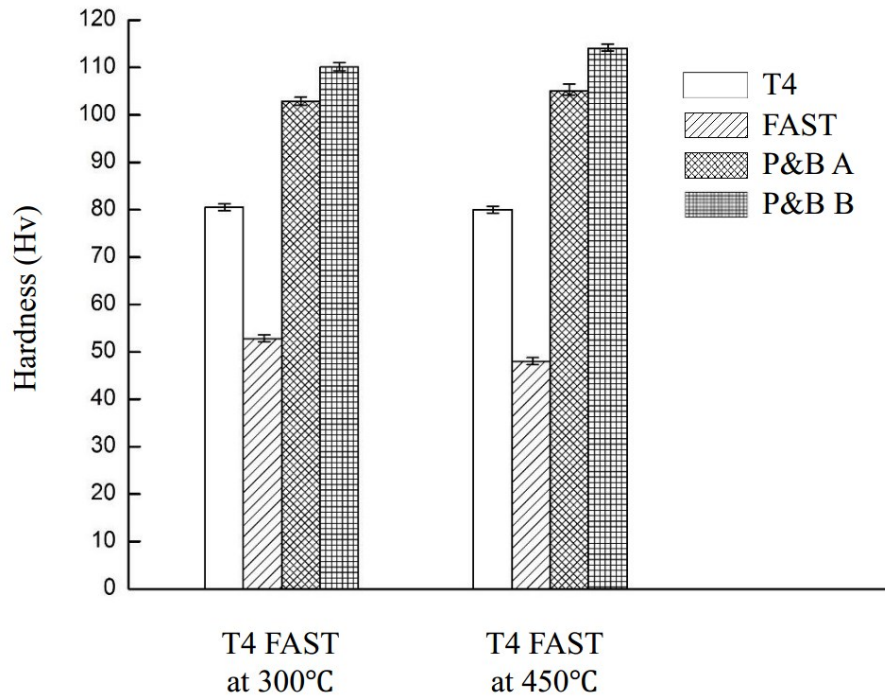


Fig 5.7 Hardness evolution of AA6082-T4 samples under the FAST process at different target temperatures of 300°C and 450°C and different paint bake cycles

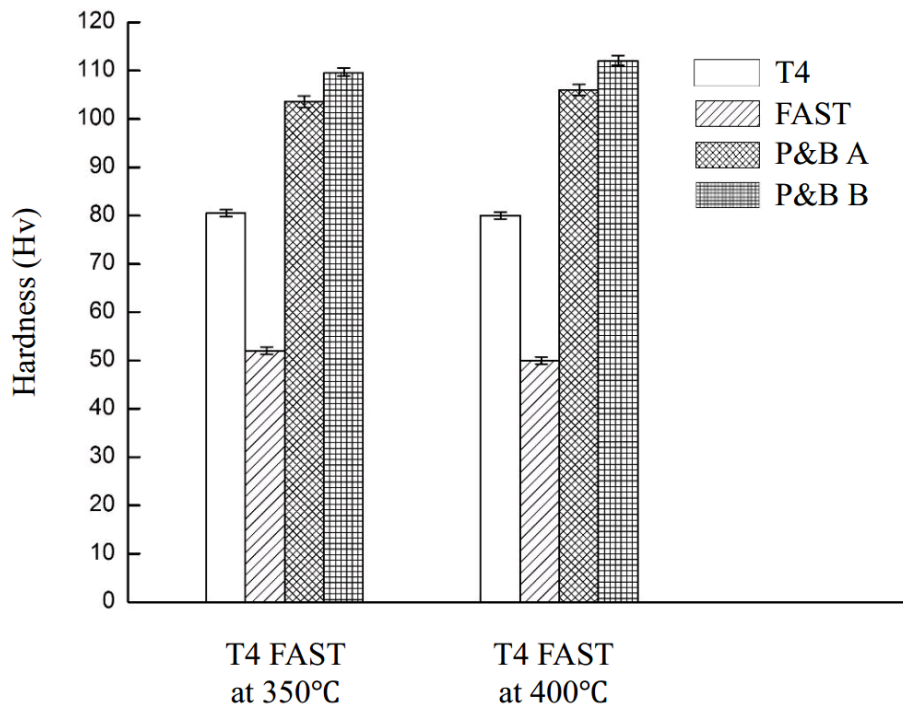


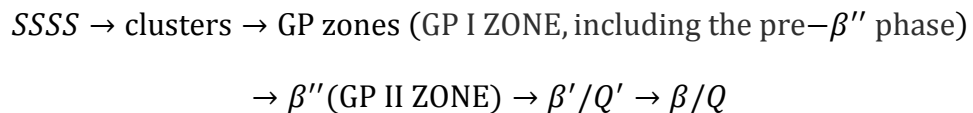
Fig 5.8 Hardness evolution of AA6082-T4 samples under the FAST process at different target temperatures of 350°C and 400°C and different paint bake cycles

compared with the solutionized ones. In addition, it was suggested that the main hardening phase of Al-Mg-Si alloys, β'' , can be generated only after the dissolution of these clusters and zones through the TEM scans of AA6082 at different precipitation conditions (Marioara et al., 2003). These factors prevent the T4 material from being formed and paint bake treated without additional pre-treatments.

In the FAST process, the metal blank is heated to an elevated temperature at an ultra-fast heating rate. For the T4 specimens, the elevated temperature not only promotes the formability of the metal blank, but also dissolves the natural ageing clusters without the detrimental effects on the microstructure given the paint bake response of the T4 specimens in all the tests. The dissolution of the clusters results in a microstructure similar to that of the solution heat treated condition of the material. As shown in Figures 5.7 and Figure 5.8, the hardness of the T4 specimens measured after application of the FAST process decreased from 80 Hv to 52.8 Hv at 300°C. This value kept decreasing with increasing forming temperature down to 48 Hv at 450°C which is the value identical to the hardness of the as-quenched specimens. This can be explained by the progressive dissolution of the natural ageing clusters in the FAST process for T4 tempered samples with increased temperature. As the clusters would be extensively dissolved, this enhances the PBR of the material and allows it to attain the high post-form strength in the subsequent paint bake cycles.

To analyse the microstructure evolutions during the FAST process, TEM scans were therefore conducted using AA6082-T4 specimens at specific FAST stages, namely the T4 specimen after the FAST process at 300°C; after the FAST process at 450°C and after the FAST process at 450°C with paint bake scheme A, as shown in Figure 5.9 (a), (b) and (c) respectively (Zhang et al., 2019).

As reviewed in Section 2.2.2, the precipitation sequence of Al-Mg-Si alloys follows:



In Figure 5.9 (a), two types of precipitates in the $\langle 100 \rangle$ Al zone axis orientation can be observed. One is dot-like with an average radius of approximately 3.9 nm and finely dispersed in the

aluminium matrix. The other is needle-shaped, which can be found by the circular end-on view and the strain contrast around them. According to the energy-dispersive X-ray spectroscopy (EDS) analysis of these dot-like spherical shaped precipitates, the ratio of Mg to Si was between 1 and 1.5. It is widely accepted that the pre- β'' has a ratio of Mg to Si of over 1 and is spherical shaped with a radius of approximately 3 nm (Marioara et al., 2003). Hence, the dot-like precipitates are determined as the pre- β'' phase considering the morphology and its

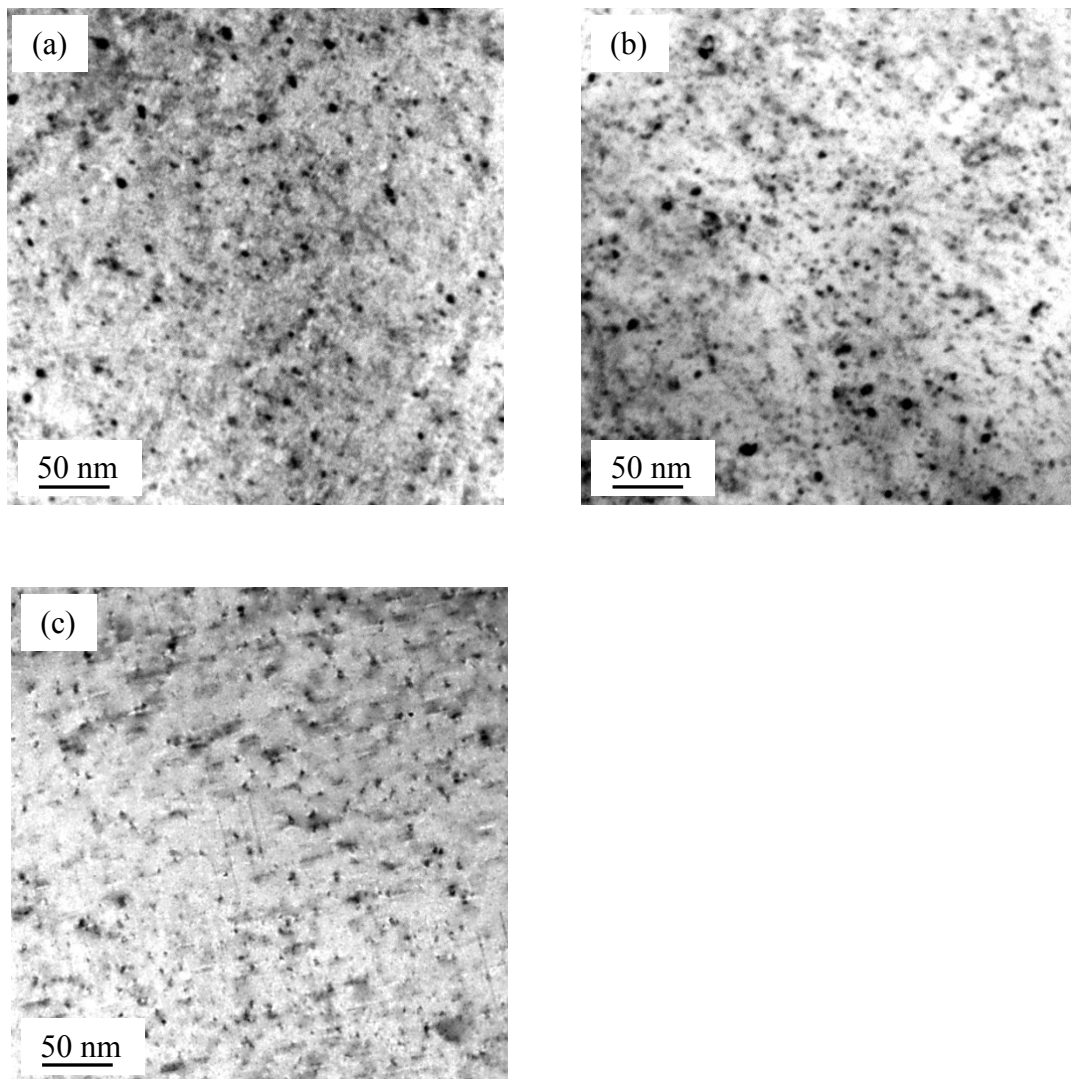


Fig 5.9 TEM micrographs of (a) the T4 specimen after the FAST process at 300°C, (b) the T4 specimen after the FAST process at 450°C and (c) the T4 specimen after the FAST process at 450°C and paint bake scheme A

composition. The needle-shaped precipitates are identified as β'' phase given their shape, orientation, strain contrast and the temperature history of the FAST process. When the temperature was increased to 450°C, it was clear that some precipitates grew in size despite an only 1.5 second increase in the heating time, as shown in Figure 5.10 (b). Meanwhile, the dissolution of the precipitates is evident, as their volume fraction is found to reduce at this condition, which illustrates that both precipitation and precipitate dissolution occur simultaneously. The difference on hardness between these two FAST processed samples, namely FAST T4 300°C and FAST T4 450°C, is only 3 to 4 Hv and both have a similar paint bake response. However, the different target temperatures lead to different microstructures in the material, which are also distinct from those observed from solution heat treated samples (Mrówka-Nowotnik et al., 2015, Mrówka-Nowotnik and Sieniawski, 2005; Humphreys et al., 2004).

Although some precipitates grow in size during the fast heating, the limited heating time due to the ultra-fast heating rate largely restricts the number of such precipitates and maintains the solute atoms in the aluminium matrix rather than consuming them to form over-sized precipitates. The β'' phase is therefore able to precipitate out of the aluminium matrix and provide an effective paint bake response. In addition, no long lath-shaped or plate-shaped precipitates were observed in Figures 5.9 (a) and (b), which are regarded as β phases in the Al-Mg-Si alloys, illustrating that overageing and annealing hardly occur in the FAST process between 300°C and 450°C. As a result, the degradation of strength was not found after the paint bake cycles. Figure 5.9 (c) shows the micrograph for the specimen after the FAST process at 450°C and paint bake scheme A. The needle-shaped precipitates can be recognised according to their circular end-on view and the strain field contrast around their face-on view. These particles were distributed homogeneously within the aluminium matrix. Considering the shape, size, orientation, relationship of the precipitates and the hardness of the sample, which was as high as the original T6 material, the needle-shaped precipitates were identified as β'' .

A schematic diagram, which summarizes the microstructure evolutions during FAST process of the T4 tempered 6082 aluminium alloy at different forming temperatures is presented in Figure 5.10.

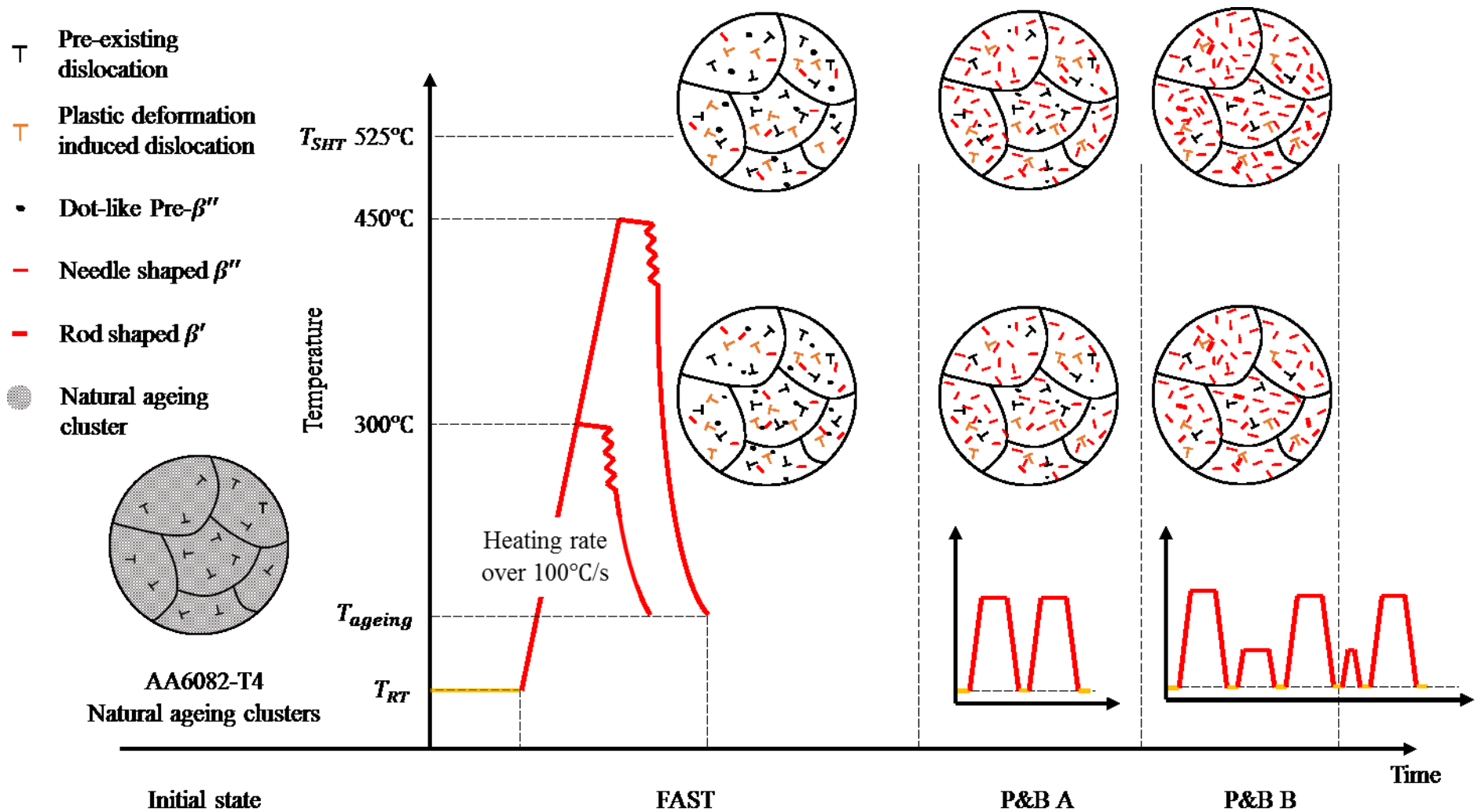


Fig 5.10 Schematic illustration of the microstructure evolutions during the FAST process of T4 tempered 6082 aluminium alloys at 300°C and 450°C

5.3.2 Effects of forming temperature on the microstructure evolutions of T6 tempered 6082 aluminium alloy during the FAST process

The heat treatment tests following the FAST process were also conducted on the as delivered AA6082-T6 at different target temperatures. Two typical forming temperatures of 300°C and 450°C were selected. Figure 5.11 shows the hardness evolution from the initial hardness, to the hardness attained after the FAST process (FAST), and finally the hardness following the application of paint bake scheme A (P&B A) and paint bake scheme B (P&B B) respectively. When the FAST process was conducted at 300°C, the hardness of the T6 temper specimens reduced from 117 Hv to 93 Hv. A hardness over 113 Hv was achieved using either paint bake cycles. When the FAST process was conducted at 450°C, the hardness of the specimens decreased to 49 Hv and increased to 106 Hv and 108 Hv after P&B A and P&B B respectively, with no additional heat treatments required.

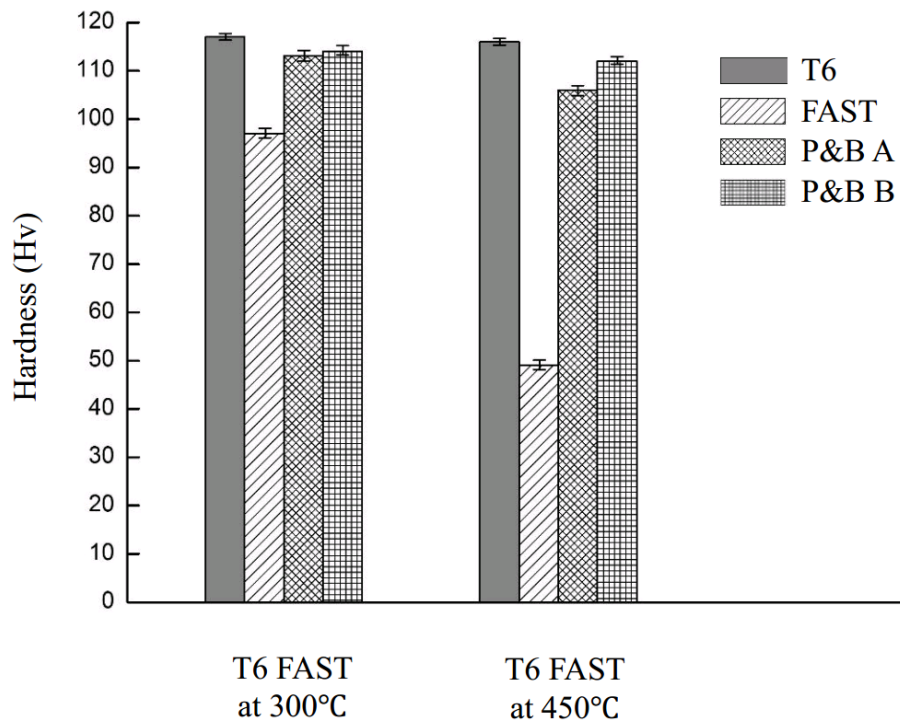


Fig 5.11 Hardness evolution of AA6082-T6 samples under the FAST process at different target temperatures of 300°C and 450°C and different paint bake cycles

For the T6 specimens, the leading phase of the microstructure is β'' where the hardness achieves a peak value of 117 Hv. As shown in Figure 5.11, the hardness of the T6 specimen after applying

FAST at 300°C only decreased by 24 Hv, implying that there was not a simple precipitate dissolution process like the dissolution of natural ageing clusters in the T4 tempered specimens. In general, the decrease in hardness of Al-Mg-Si alloys is mainly attributed to two reasons. The first is the dissolution of the existing hardening phases such as the solution heat treatment of the material in which all the precipitates are dissolved in the aluminium matrix and the dissolution of the natural ageing clusters. The second is the precipitates over-growing in size and decreasing in number density such as the over ageing process as explained in Section 5.2. Considering the target temperature of the FAST process is greater than the artificial ageing temperature of 6xxx series aluminium alloys, which is between 170°C to 190°C, and lower than the solution heat treatment temperature of 525°C, it could be deduced that part of the pre-existing hardening phase β'' grew to β' or even β phases, and the hardness thus decreased. Meanwhile, the remainder of the pre-existing β'' phase would remain. As the limited heating time minimizes the consumption of solute atoms, both GP zones and pre- β'' would transform to β'' phases in the paint bake cycles, providing the high post-form strength.

When the temperature was increased to 450°C, the hardness of the T6 samples reduced to 48 Hv, which is identical to the T4 samples tested at the same forming condition. Meanwhile, the paint bake responses of the T6 temper specimens are similar to the T4 temper ones, in which the full strength could be regained after the paint bake cycles. This demonstrates that the dissolution dominated the microstructure evolution of the T6 temper specimens at this temperature as with the T4 temper specimens. Meanwhile, the ultra-fast heating rate significant reduces the exposure of the material to the unfavourable elevated temperatures and it is supposed to minimize the coarsening of the pre-existing hardening phases such as the β'' into the stable β phase. The detrimental effects could hardly be found on the paint bake response of the FAST processed T6 specimens at 450°C. This would be further explained by the specimens tested under the slow heating process to 450°C as presented in Section 5.3.3.

Although the hardness of the T6 temper specimens after FAST at 450°C was almost the same as the as-quenched condition, a difference on microstructure may exist between these two conditions, since the temperature is not as high as the solution heat treatment (SHT) temperature (T_{SHT}) and the samples are not soaked at T_{SHT} for a long time during the FAST process. According to the study of solution heat treatment of AA6082 (Garrett et al., 2005), the

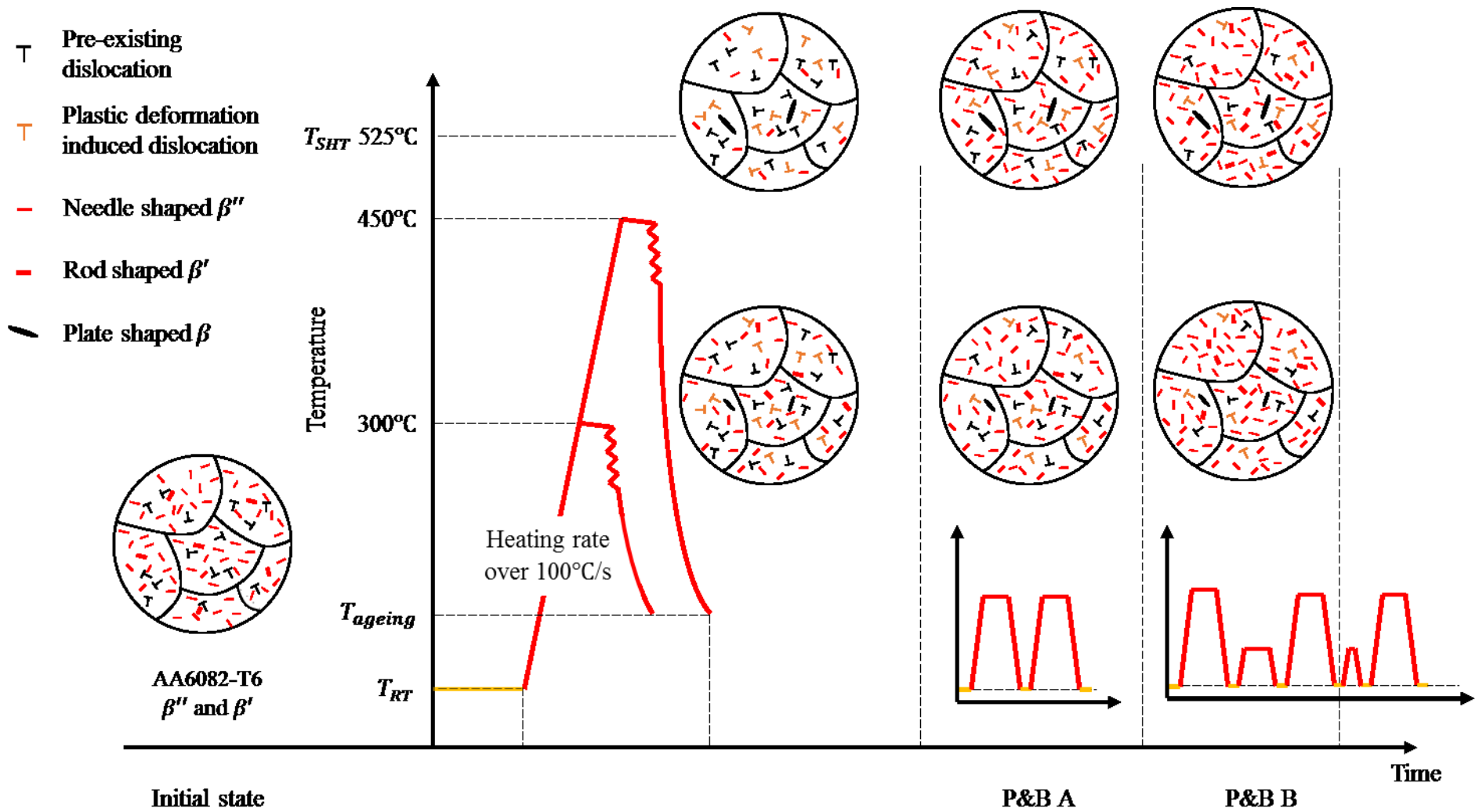


Fig 5.12 Schematic illustration of the microstructure evolutions during the FAST process of T6 tempered 6082 aluminium alloys at 300°C and 450°C

precipitates dissolve into the material and diffuse throughout the whole structure during the SHT and a more homogeneous microstructure could be obtained with increased soaking time. Despite the FAST process at 450 °C being unable to provide a highly homogeneous microstructure as with solutionizing conditions, the sufficiently dissolved pre-existing precipitates such as the β'' , β' and the minimized undissolved β phase contribute to the high paint bake response as well as the high post-form strength of the material during the paint bake cycles. In addition, it can be found that the hardness of the T6 specimens tested at 450°C after paint bake cycles is approximately 5 Hv lower than those tested at 300°C with the same paint bake treatment. This implies that the β phase that is generated during the heating process could further grow in size compared with the samples fast heated to 300°C, and cause the slight degradation on the final hardness of the material.

The microstructure evolution during the FAST process at 300°C and 450°C for the T6 tempered material consist of several distinct reactions, where the phase formation, dissolution and alteration of number density occur simultaneously, especially given the initial microstructure of the material which contains plenty of metastable hardening phase β'' and the target temperature of the FAST process is between the normal ageing temperature and the solution heat treatment temperature. According to the analysis, a summative diagram of microstructure evolutions can be drawn in Figure 5.12.

5.3.3 Effects of slow heating rate on the microstructure evolutions during the traditional warm and hot stamping processes of AA6082-T4 and T6

Heat treatment tests following the traditional warm/hot stamping processes with slow heating rate at 1°C/s were conducted. The hardness evolution of the T4 and T6 tempered alloy from the initial hardness, to the hardness after the slow heating process (SLOW) to 300°C and after two different paint bake schemes are presented in Figure 5.13.

When the samples were slow heated to 300°C, the hardness of the T4 tempered sample slightly increased from 79.5 Hv to 82 Hv while that of the T6 tempered sample decreased from 117 Hv to 88 Hv. Unlike the FAST process, a very limited paint bake response (PBR) can be found for both materials. The hardness increased by only 2 Hv for the T4 tempered specimens after P&B A and no further improvement was observed even when a longer paint bake process (P&B B)

was applied. For the T6 tempered specimens, the PBR is 3.7 Hv for the P&B A and 4.2 Hv for the P&B B.

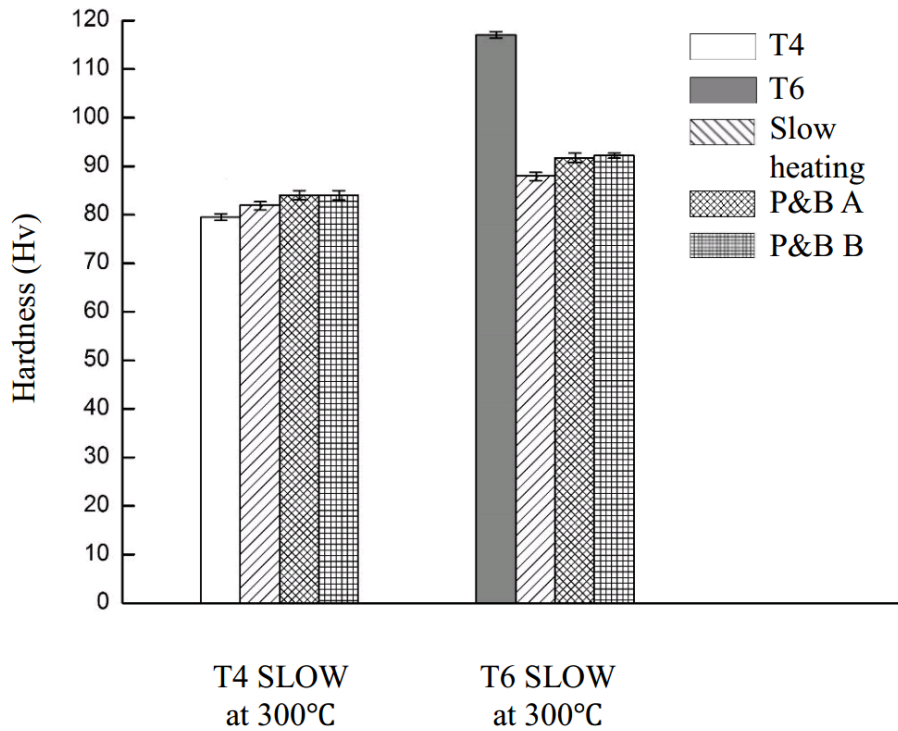


Fig 5.13 Hardness evolution of T4 and T6 tempered AA6082 under a low heating process at 1°C/s to target temperature of 300°C with different paint bake cycles

In general, the strengthening mechanism of precipitation hardening aluminium alloys is that the precipitates and the stress fields caused by lattice distortion around the precipitates impede the movement of the dislocations. As the dominant hardening phase of AA6082, β'' is a metastable phase compared with other types of precipitates such as β' and β during heat treatment (Ninive et al., 2014). The growth in the size of β'' and the decrease in its number density cannot be avoided given the long heating time of several minutes and the high temperature which is higher than the normal artificial ageing temperature but lower than the solution treatment temperature of the material in the heating processes with slow heating rate of 1°C/s.

For the T4 tempered material, the natural ageing cluster was dissolved during heating considering the target temperature of 300°C. Since the hardness almost remained unchanged for the material after the heating process, it was deduced that the precipitation hardening and over-ageing, where the precipitates over-grow in size, occurred simultaneously, while neither of them dominates the whole process. The effects of these two processes on the material hardness

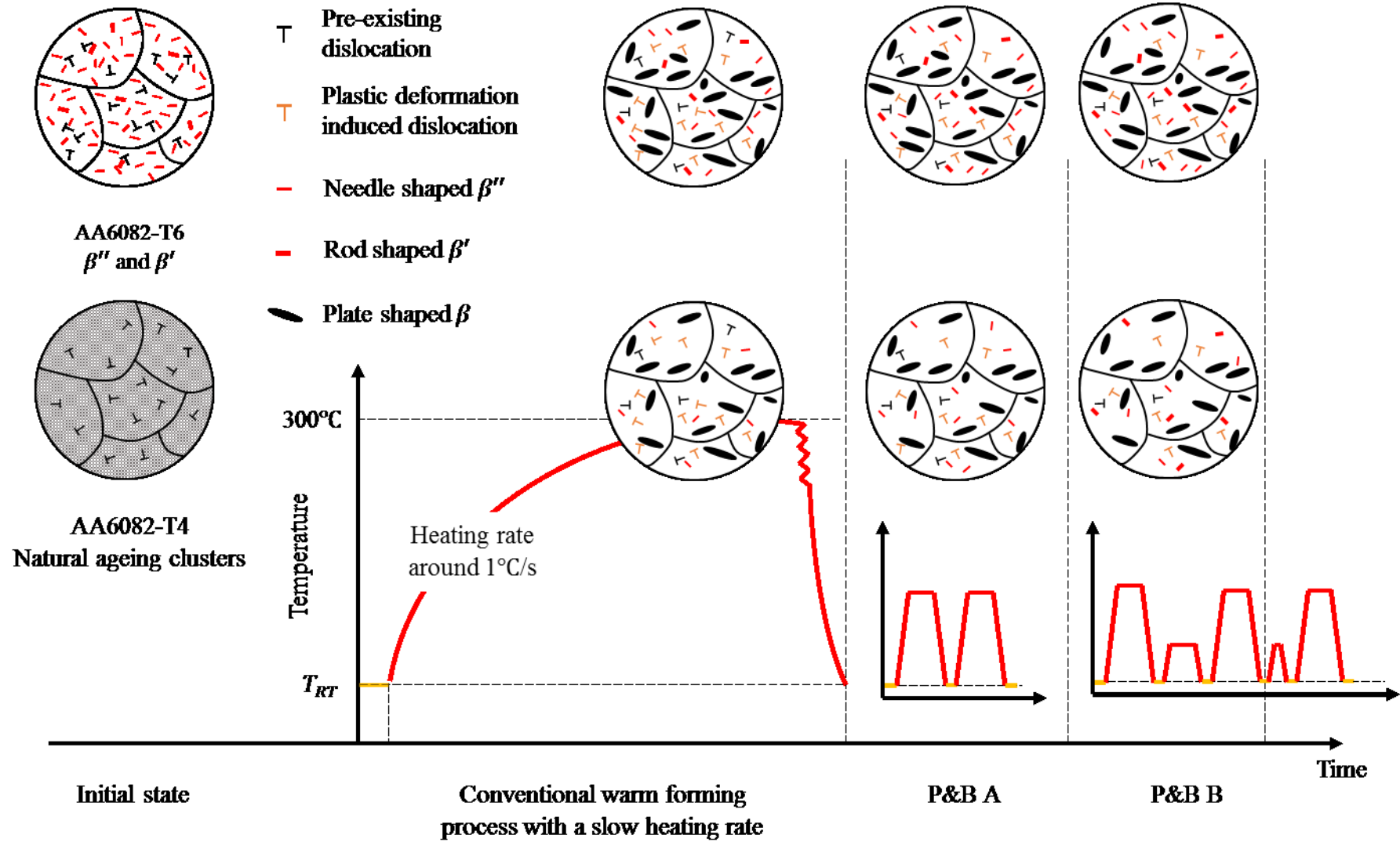


Fig 5.14 Schematic illustration of the microstructure evolutions during the conventional warm forming process of T4 and T6 tempered 6082 aluminium alloys at 300°C

counteract each other and a quasi-static state of the material was achieved. The PBR was found only 2 Hv during both paint bake treatments, therefore the material is supposed to be at the over-aged condition, where the stable hardening phase β was extensively generated consuming the solute atoms in the aluminium matrix and the specimens lost response to the paint bake treatment.

For the T6 specimen, the pre-existing hardening phase β'' was abundant before heating and the forming temperature of 300°C was much lower than the solutionizing temperature of 525°C to dissolve these particles, and so the remaining hardness after the heating process was higher than that for the T4 specimens by 6 Hv. However, the slow heating rate prolonged the heating time and led to the overgrowth of the existing precipitates, resulting in the degradation on hardness after heating and the limited PBR as the T4 tempered specimens. The schematic diagram summarizing the microstructure evolutions during conventional warm forming process of T4 and T6 tempered 6082 aluminium alloy at 300°C is shown in Figure 5.14.

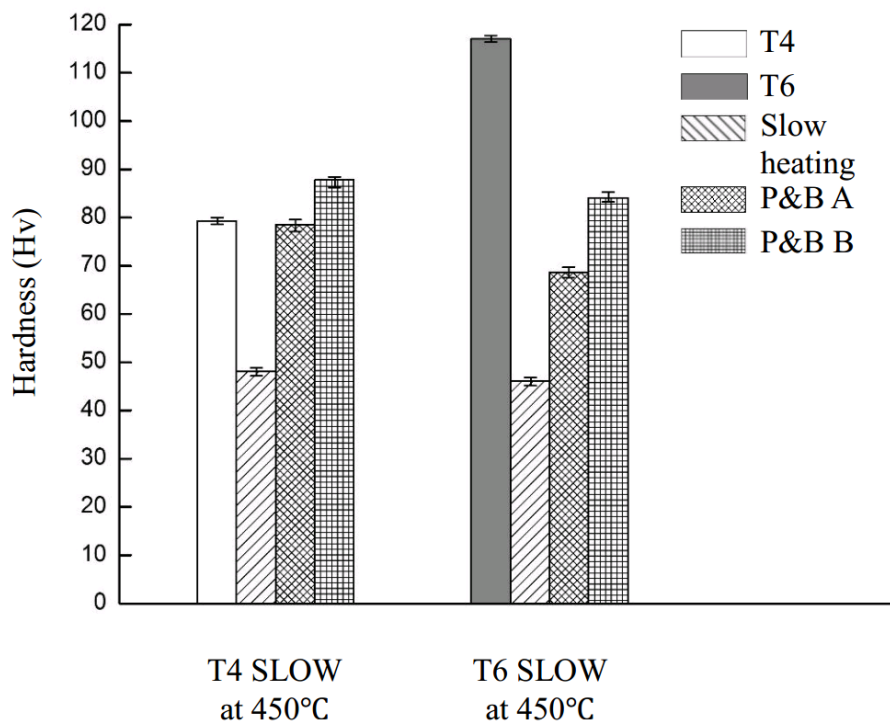


Fig 5.15 Hardness evolution of T4 and T6 tempered AA6082 under a low heating process at 1°C/s to target temperature of 450°C with different paint bake cycles

When the target temperature of the slow heating process was increased to 450°C, the hardness evolution of the T4 and T6 tempered alloy from the initial hardness, to the hardness after the

slow heating process (SLOW) and after two different paint bake schemes are presented in Figure 5.15. Similar to the FAST process at 450°C, the hardness of both T4 and T6 tempered samples dropped to 47 Hv after heating. However, the hardness of both types of materials can be hardly increased to over 90 Hv after the paint bake treatments. The hardness was only 78.4 Hv and 87.8 Hv for the AA6082-T4 and 68.6 Hv and 84.1 Hv for the AA6082-T6 after P&B A and P&B B respectively.

Compared with the specimens tested at 300°C under the slow heating conditions, the remarkable decrease on hardness after heating to 450°C and subsequent increase on hardness after paint bake cycles demonstrates that the dissolution of the pre-existing precipitates, i.e. natural ageing clusters for the T4 tempered material and β'' and β' for the T6 tempered material, is more pronounced when heated to 450°C. Therefore, the precipitation hardening and a PBR over 39 Hv could be observed in both T4 and T6 tempered materials. Meanwhile, strength of the AA6082-T6 sample is lower than the AA6082-T4 sample after paint bake cycles by 9.8 Hv after P&B A and 3.7 Hv after P&B B respectively. This could be explained by the higher number density of the β phase in the T6 tempered specimens compared to the T4 tempered specimens after slow heating to 450°C. The number density of β'' is much higher in the T6 tempered material before the heating process. This metastable phase strengthens the material initially, but the larger number of β'' means that more β will be transformed to and degrade the strength of the material. Meanwhile, 450°C is not sufficiently high to dissolve these stable β phase that was generated during the slow heating process, which leads to the lower hardness of the T6 tempered specimens after paint bake treatments compared with the T4 tempered specimens.

In addition, the higher target temperature of 450°C leads to a longer heating time and more β phase precipitates are generated during the slow heating process especially for the T6 tempered specimens. As a result, the strength of AA6082-T6 samples after heating to 450°C and paint bake treatment is less than the T6 tempered samples processed at 300°C by 23 Hv after P&B A and 8 Hv after P&B B. Moreover, recrystallization also occurs during the slow heating to 450°C, which leads to a worse paint bake response and softer material compared with the specimens slow heated to 300°C. According to the Electron Back-Scattered Diffraction (EBSD) and TEM analysis of non-isothermal annealed AA6451, recrystallization was found to initiate at 300°C

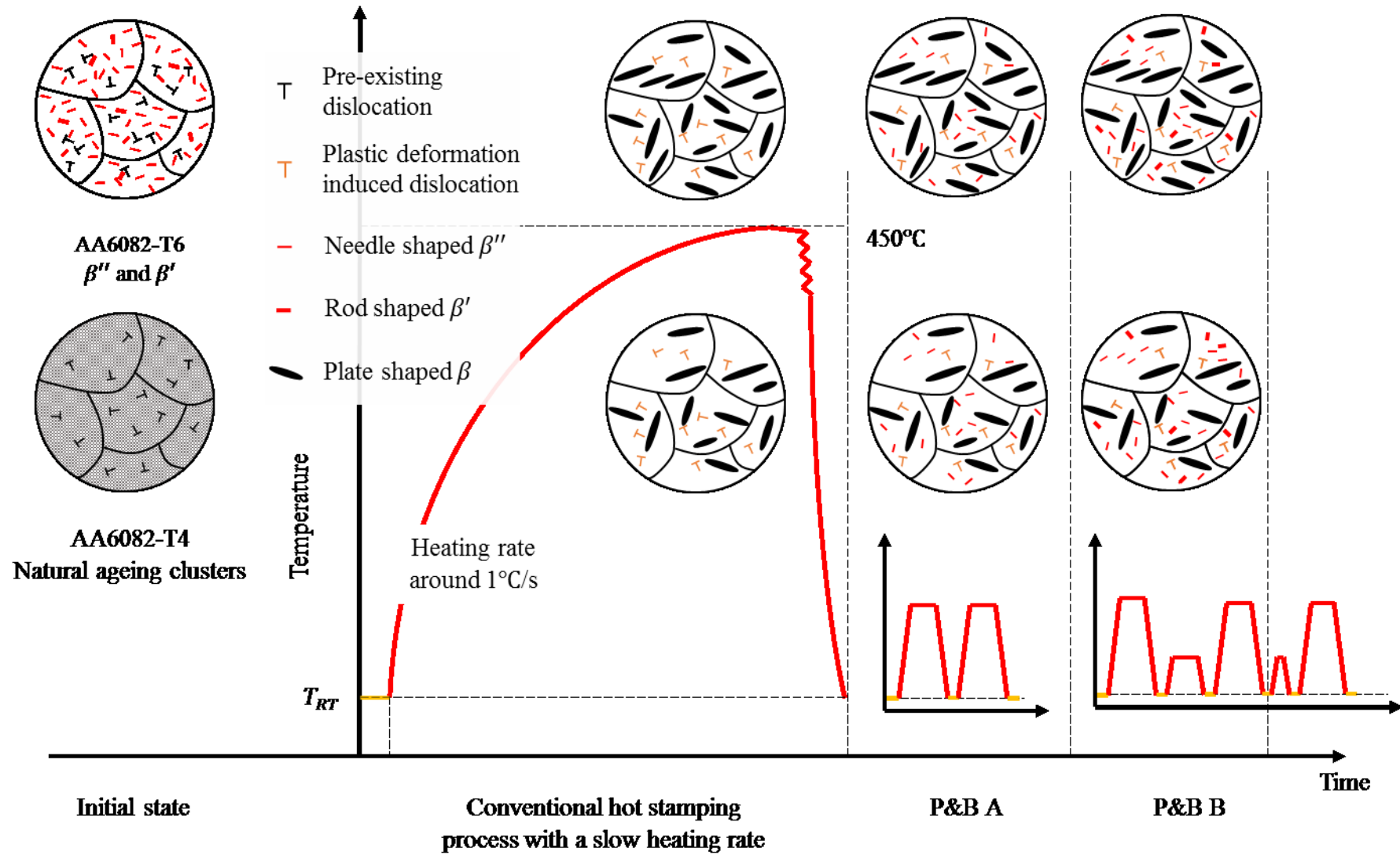


Fig 5.16 Schematic illustration of the microstructure evolutions during the conventional warm forming process of T4 and T6 tempered 6082 aluminium alloys at 450°C

and proceeds through a nucleation and growth mechanism. A recrystallized dislocation-free microstructure was achieved at 380°C (Sepehrband et al., 2015).

The schematic diagram demonstrating the microstructure evolutions during conventional hot stamping process of T4 and T6 tempered 6082 aluminium alloy at 450°C is shown in Figure 5.16.

Paint bake treatment is usually claimed to be too short with too low a temperature for the precipitate hardening potential of aluminium alloys to be exploited in such treatment (Birol, 2006). However, this could be due to the pre-treatment or prior heating process not being suitable for the subsequent paint bake cycles. For the age hardening aluminium alloys, once the precipitates over-grow in size extensively during the slow heating process, the full strength can no longer be regained through the paint bake treatments or other ageing processes, and would necessitate a full solution heat treatment of the metal blank. The FAST process is able to maintain the pre-existing hardening phases of the specimens, enhancing the paint bake response and eliminating the solutionizing requirement of the materials simultaneously through the ultra-fast heating and precision processing parameters control. This demonstrates that the heating rate is more critical than the forming temperature for heat treatable aluminium alloys during warm and hot stamping processes in terms of the post-form strength, and that paint bake cycles are sufficient for 6xxx series aluminium alloys to regain their full strength, when the appropriate forming technology, such as FAST, is applied.

5.4 Thermo-mechanical properties of T4 and T6 tempered 6082 aluminium alloys under ultra-fast heating conditions

The thermo-mechanical properties of AA6082-T4 and T6 under ultra-fast heating conditions were obtained from uniaxial tensile tests. Figure 5.17 shows the experimental results of the materials tested at different temperatures (300°C, 350°C, 400°C and 450°C) at a strain rate of 1/s. The flow curves for AA6082-T4 and T6 at room temperature can be found in Appendix 2.

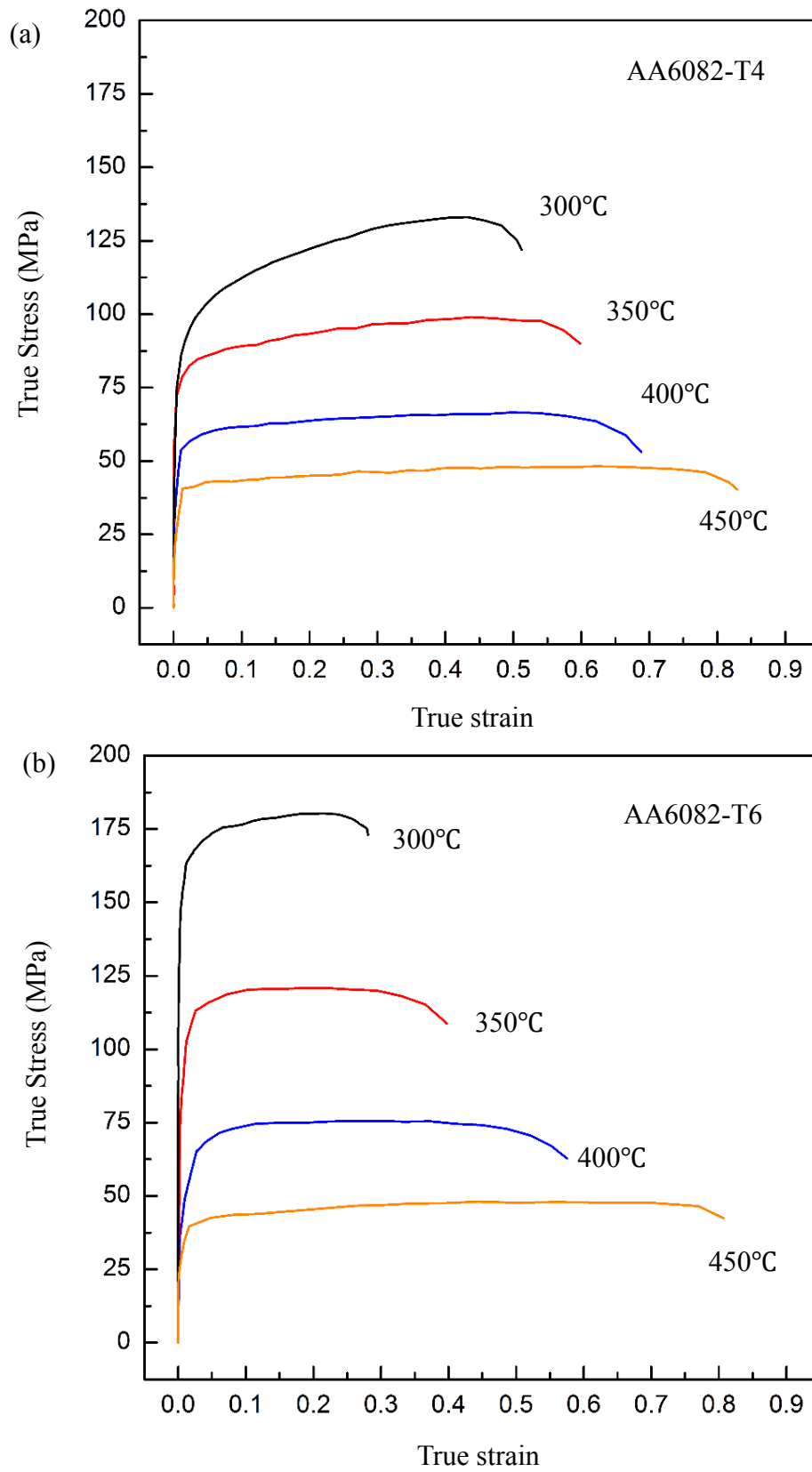


Fig 5.17 Stress-strain curves of (a) AA6082-T4 and (b) AA6082-T6 under the ultra-fast heating condition with different target temperatures at a strain rate of 1/s

AA6082-T4 and T6 showed strong temperature sensitivity under the test conditions. The flow stress of both materials decreased and the ductility increased remarkably with increasing temperature. The FAST process achieved a true fracture strain of 0.50 and 0.32 for the T4 and T6 specimens at 300°C with ultimate tensile strength (UTS) of 133.1 MPa and 180.4 MPa respectively. When the FAST process was conducted at 450°C, the true fracture strain as high as 0.85 for both T4 and T6 specimens was achieved and the UTS was approximately 48 MPa. The ultimate tensile strength and the failure strain are extracted from Figure 5.11 and plotted in Figure 5.18.

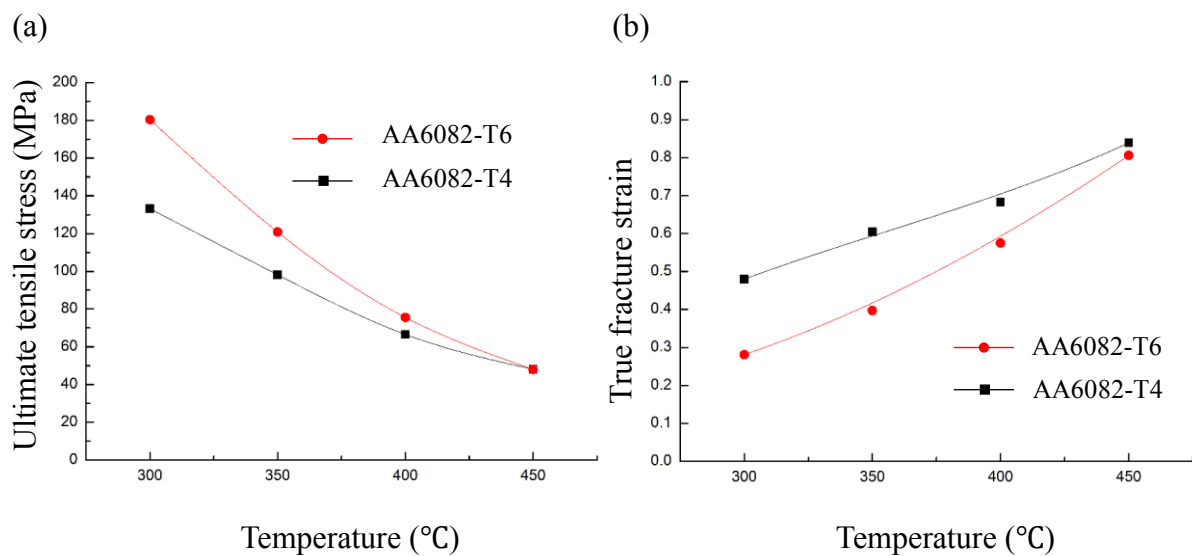


Fig 5.18 (a) Ultimate tensile stress (UTS) and (b) true fracture strain of AA6082-T4 and AA6082-T6 under the ultra-fast heating condition with different target temperatures at a strain rate of 1/s

At elevated temperatures, the deformation mechanisms of aluminium alloys are thermally activated (Hosford and Caddell, 2011; Kashyap et al., 2009). When the forming temperature increases, the enhanced thermal vibration of the lattice results in the lower strength of the obstacles that impedes the movement of the dislocations. As the dislocation mobility is improved, the material becomes softer and more ductile. In addition, additional slip systems can be activated when the forming temperature is increased to 300°C. According to a study of AA6016-T4, additional slip systems were observed when the forming temperature was higher than 250°C (Kurukuri et al., 2009). In these activated slip planes, as the deformation proceeds, the recovery becomes more obvious and reduces the dislocation density, which results in the lower flow stress.

As shown in Figure 5.17, the work hardening of the AA6082-T4 is more evident compared with T6 tempered material under the same temperature. The flow behaviour of heat treatable aluminium alloys at elevated temperatures is influenced by multiple dynamic mechanisms such as the recovery, strain hardening, precipitation and/or precipitates coarsening. For the AA6082-T6, the work hardening is diminished due to precipitate coarsening, since the metastable hardening phase β'' in the T6 material is more prone to coarsening and softens the material during the test. In addition, it was reported the dynamic recovery effect increases with increasing temperature and varies with the material temper. The dynamic recovery was found to be more pronounced for the material in T6 temper compared with the W and T4 tempers when forming at 300°C, which led to the lower hardening effect during the deformation (Lee et al., 2004).

In addition, it can be found that the difference between the flow behaviour of AA6082 in T4 and T6 tempers becomes smaller with increased forming temperature and becomes almost identical at 450°C, which has good agreement with the hardness measurements at the same forming condition. When the forming temperature increases to 450°C, as discussed in Section 5.3, the dissolution of the precipitates dominates the microstructure evolution, the precipitates in both T4 and T6 temper specimens are substantially dissolved, which results in the similar microstructure as well as the flow behaviour.

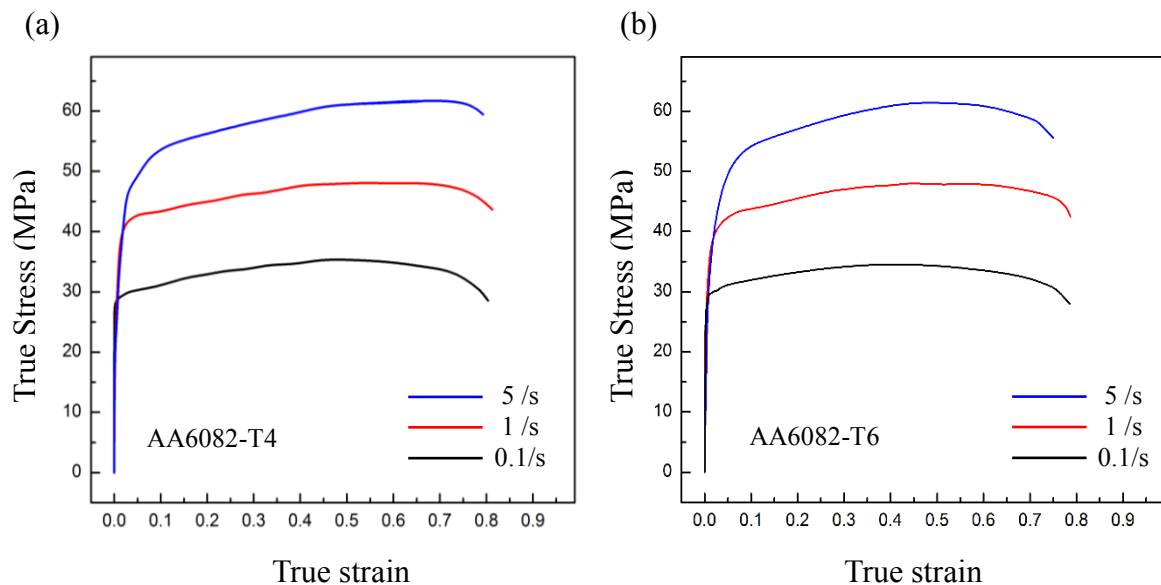


Fig 5.19 Stress-strain curves of (a) AA6082-T4 and (b) AA6082-T6 under the ultra-fast heating condition with different strain rates at 450°C

The effect of strain rate at a temperature of 450°C is shown in Figure 5.19. In general, the flow stress increased and the true fracture strain reduced with increasing strain rate from 0.1/s to 5/s, which demonstrates the strain rate sensitivity of the material at 450°C. The increased flow stress attributes to the strain rate hardening effect, which increases the work hardening capability of the material. Meanwhile, the strain rate can be understood in terms of the duration for the specimens exposed at elevated temperatures. Lower strain rate allows more time for the static recovery and results in a reduced flow stress. In addition, the recovery leads to the annihilation of dislocations, which reduces the localized straining and results in better ductility at lower strain rate (Kumar et al., 2014; Lin et al., 2005).

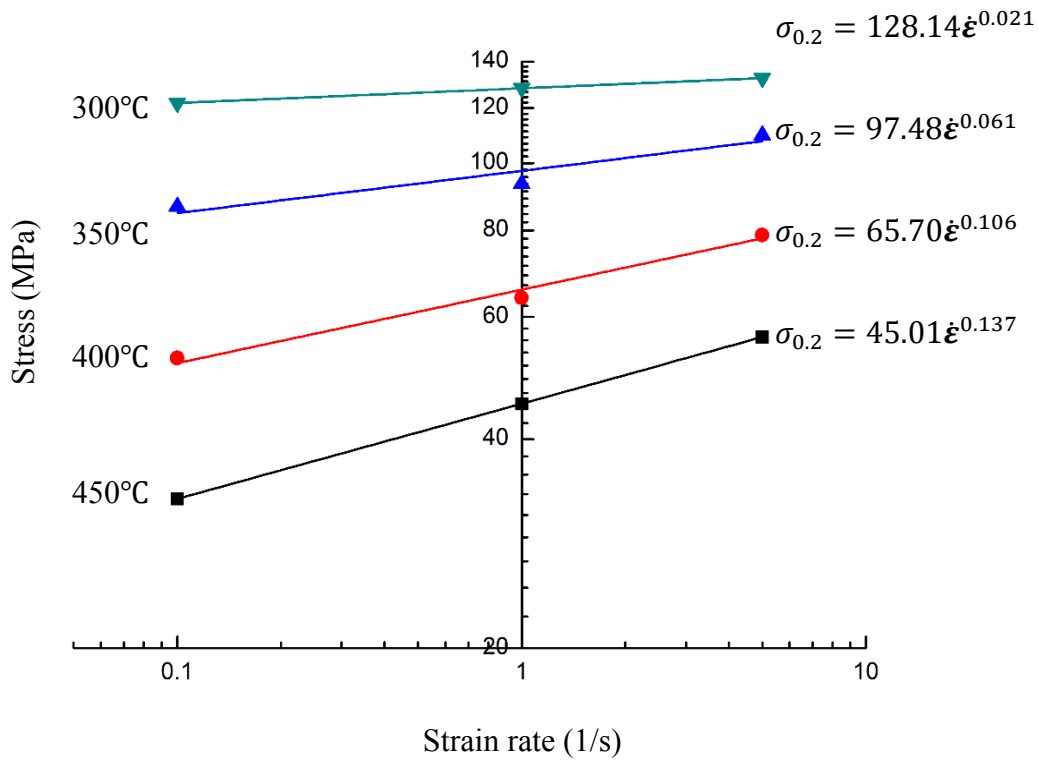


Fig 5.20 Flow stress of AA6082-T4 at a strain level of 0.2 with different strain rates (0.1/s, 1/s and 5/s) at different temperatures

Figure 5.20 summarizes the stress of AA6082-T4 at a strain level of 0.2 for different strain rates and forming temperatures. The stress and strain rate was plotted on a log-log scale. The linear relationship suggests the power-law viscoplastic behaviour of the material. The slope of the line represents the strain rate hardening exponent m , which indicates the hardening effects of the material during the deformation and benefit for the uniform deformation during the forming

processes (Hosford and Caddell, 2011). It is clear that the strain rate sensitivity is increased with the increasing forming temperature for the AA6082-T4 and the m value raised from 0.021 to 0.137 when the forming temperature was increased from 300°C to 450°C.

5.5 Application of FAST on AA6082 in other pre-aged tempers

In addition to the naturally aged T4 and artificially aged T6 temper specimens, the FAST was applied to the AA6082 with other artificial aged conditions. A new material temper TX dedicated to the FAST process was proposed where the specimens are solution heat treated and artificially aged to different levels. Four TX temper materials, namely TX₁ (180°C/2 min), TX₂ (180°C/5 min), TX₃ (180°C/10 min) and TX₄ (180°C/40 min) were prepared in this study. The initial hardness of the specimens after the ageing treatment are 60 Hv, 70 Hv, 80 Hv and 110 Hv, as shown in Figure 5.5 and Figure 5.21.

The heat treatment tests following the FAST process were conducted at two typical forming temperatures of 300°C and 450°C for the four types of TX tempered samples. The samples were prepared and stored at room temperature for 7 days before the tests. The hardness evolution of the specimens during the FAST process at 300°C and two paint bake cycles are summarized in Figure 5.21.

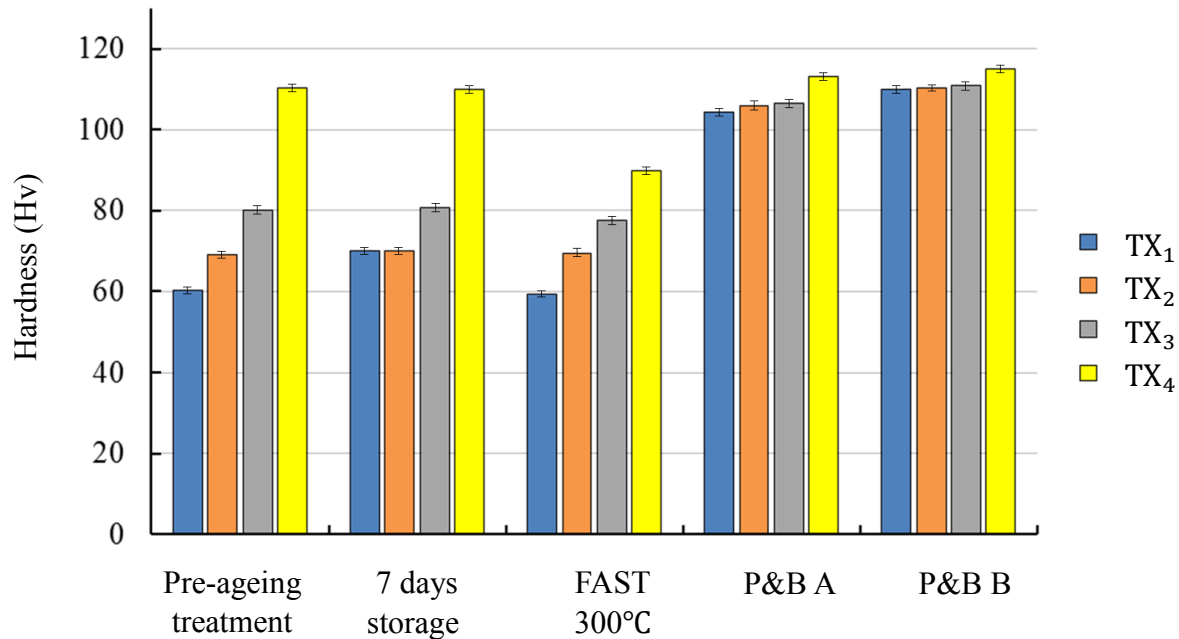


Fig 5.21 Hardness evolution of AA6082 in different TX tempers (TX₁ , TX₂, TX₃ and TX₄) under the FAST process at 300°C with different paint bake cycles

As presented in Section 5.2.2, the hardness of the samples after solution heat treatment and artificial ageing at 180°C for 5 minutes or greater would remain stable during the storage due to the precipitation hardening particles that suppress the formation of natural ageing clusters. The hardness of all samples except for those in the TX₁ temper remained unchanged during storage, while the hardness of TX₁ tempered samples increased from 60.4 Hv to 70 Hv during storage. When the FAST process was applied, the hardness of the TX₁ tempered specimens reduced to 59.5 Hv. For the TX₂ and TX₃ tempered specimens, the initial hardness was unchanged at 70 Hv and 80 Hv respectively after the FAST process. Only the TX₄ temper specimens witnessed a decreased hardness from 110.2 Hv to 89.9 Hv. In the meantime, the adequate increase due to paint bake cycles can be found on all four types of specimens after both paint bake treatments. For the TX₁ samples, the hardness increased to 104.3 Hv after P&B A and 110.1 Hv after P&B B. The hardness is found to be slightly higher in TX₂ and TX₃ samples. The TX₄ samples achieved the maximum hardness compared with three other types after the paint bake cycles, where the hardness was as high as 113.2 Hv and 115.4 Hv after P&B A and P&B B respectively, or more than 95% of the as-delivered T6 condition.

As discussed in Section 5.3.1 and 5.3.2, the hardness evolution of the specimens under the FAST process at 300°C is comprised of different reactions of the precipitation particles and the dominant mechanism is highly dependent on the initial material temper. For example, the reaction of the TX₁ tempered samples during the FAST process is similar to that of the T4 tempered samples, where the dissolution of natural ageing cluster is primary, especially given the TX₁ samples are still influenced by the room temperature storage with increased hardness. Although the initial hardness is lower and the artificial ageing time is much shorter compared with the as-delivered T6 temper specimens, the performance of TX₄ specimens resembles that of the T6 tempered specimens, in which the hardness reduces by 20 Hv after the FAST process. This implies that part of the existing β'' grow in size and part of the hardening phase remains, leading to the reduction on the hardness after FAST. For the TX₂ and TX₃ tempers, it can be deduced that the cumulative effect of precipitation hardening process and existing hardening precipitate coarsening leads to the unchanged hardness before and after FAST. Considering the PBR of all types of samples, FAST demonstrates the capability of retaining the existing precipitates and minimizing the coarsening in the microstructure during the heating and forming

processes and sufficient primary hardening phase β'' can be generated during the paint bake cycles.

The hardness evolution of the four types of TX tempered specimens after the FAST process at 450 °C is shown in Figure 5.22. The hardness of all TX tempered samples reduced to approximately 48 Hv and increased to over 105 Hv after P&B A and over 110 Hv after P&B B. The paint bake response of TX₁ is the highest compared with the other three types of TX tempered specimens, in which the hardness values achieved were as high as 110 Hv and 117 Hv after two paint bake cycles respectively. Meanwhile, it is noticed that the PBR and the final hardness gradually decreases with the increased pre-ageing time from TX₁ to TX₄. Although the difference is only within 5 Hv, the trend is clear according to the repeated tests. For the TX₄ samples, the hardness increased to 106 Hv after P&B A and 112 Hv after P&B B.

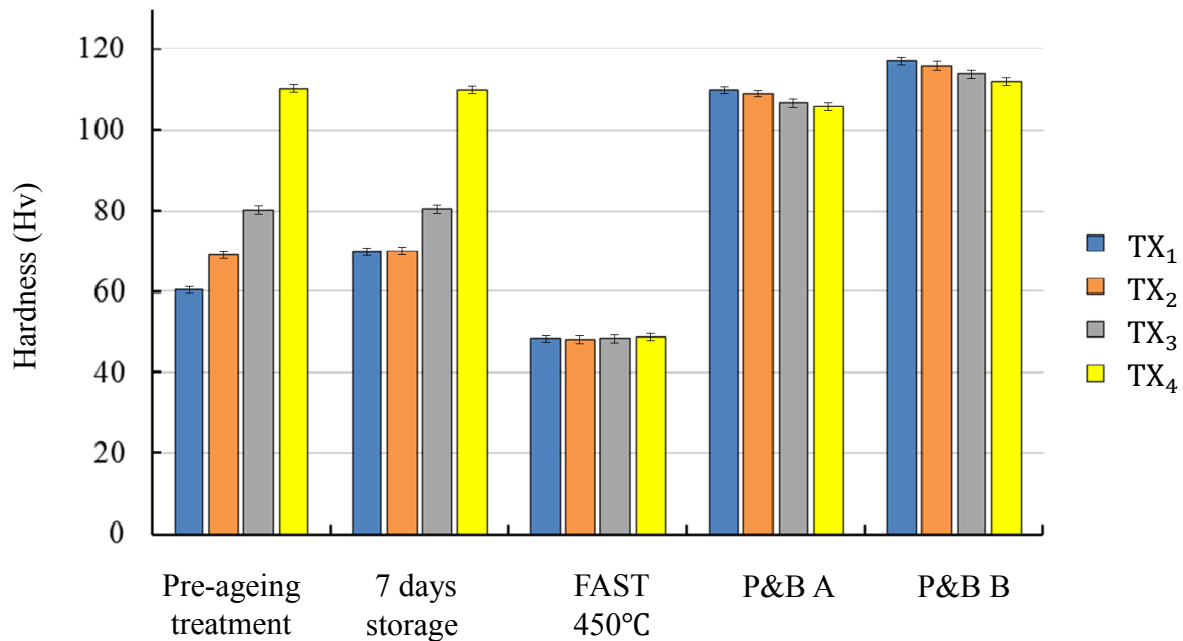


Fig 5.22 Hardness evolution of AA6082 in different TX tempers (TX₁ , TX₂, TX₃ and TX₄) under the FAST process at 450°C with different paint bake cycles

The mechanism of FAST at 450°C is more unified for all types of TX tempered materials, where the dissolution of the pre-existing precipitation particles dominates the microstructure evolution. The hardness evolution after the FAST process and the paint bake cycles are similar to the T4 and T6 temper materials. As explained in Section 5.3.2, 450°C is not sufficiently high to

dissolve all the precipitates during the ultra-fast heating process. Instead, the coarsening of precipitates could occur simultaneously. The longer pre artificial ageing time of the TX₄ tempered material results in more hardening phase β'' within the material initially, and the more apparent reduction of strength once the hardening phase coarsens after the FAST process.

For actual production, the T4 tempered material should be utilized instead of T6 material when higher formability is required, and FAST processed at 450°C, as the paint bake response is better and the cost of raw material production of T4 material is much lower. However, the T6 tempered material is able to remain higher strength after the FAST process and results in quicker recover to its full strength during the paint bake cycles when the process is conducted at 300°C. In addition, the TX tempered material provides a flexible approach in the material selection of the FAST process. The material can be produced with strength at different levels and the FAST process is able to maintain the strength after heating and forming. Therefore, the aluminium sheet can be tailor manufactured into different TX tempered conditions according to the requirement on formability and existing paint bake cycles of the vehicle manufacturers. Through making the most of the paint bake cycles to regain the full strength of the formed components, the TX temper can further reduce the cost of the FAST process for blank manufacturers and press shops.

5.6 Summary

In this chapter, the precipitation hardening behaviour of AA6082 was studied. 180°C was the optimized artificial temperature and the peak hardness 117 Hv could be achieved in 9 hours. Higher artificial ageing temperature, such as 220°C, facilitated the precipitation hardening process to 20 minutes, while that was at the expense of a reduction in peak hardness by 10%. The artificial ageing at 180°C and 220°C after the solution heat treatment can suppress the influence of subsequent natural ageing due to the existence of the precipitation hardening phases.

The mechanism of FAST was investigated through the heat treatment tests and the TEM scans of the FAST processed specimens. For the naturally aged AA6082-T4, the FAST process mainly dissolves the natural ageing cluster and generates the pre- β'' phase, which facilitates the precipitation hardening response of the material. For the artificial aged AA6082-T6, the FAST process cause several different reactions of microstructure simultaneously. When the forming

temperature is 300°C, part of the pre-existing hardening phase β'' remains and precipitate coarsening occurs. Due to the ultra-fast heating process, the coarsening is minimized. When the forming temperature is 450°C, the dissolution of the precipitates dominates the evolution of the microstructure. As the detrimental effects of the specimens exposed at inadaptably elevated temperatures are suppressed in the FAST process, the desired post-form strength can be achieved with only the paint bake cycles rather than solution heat treatment and post-form artificial ageing. The FAST process was further applied to the AA6082 in other pre-aged tempers. It was found that FAST could maintain the initial strength of the material throughout the process, and sufficient post-form strength can be achieved by paint bake cycles. Therefore, the aluminium sheet can be tailor manufactured instead of using the T4 and T6 tempers, making the most of the paint bake cycles and reducing the cost of the process.

The ductility of AA6082 under the ultra-fast heating condition was studied and the effects of temperature, strain rate and material temper were assessed. Through heating the metal blank to the elevated temperature, FAST provides a much lower flow stress during stretching and a larger elongation to failure compared with the cold stamping condition. The failure strain is over 0.50 and 0.32 for the AA6082-T4 and T6 at 300°C and as high as 0.85 for both materials at 450°C.

Chapter 6

Forming trials of the FAST process: study of the formed components and the benchmark study on cycle time

6.1 Introduction

This chapter focuses on the forming trials of the FAST process using the dedicated pilot production line Uni-Form. It consists of the study of the formed components and a benchmark study on the manufacturing cycle time. The properties of the formed U-shape components, including springback, post-form strength and surface roughness, are presented. The effects of forming temperature, forming speed and material temper were analysed in order to characterise the FAST process in practical forming scenarios. A benchmark study of the manufacturing cycle time was conducted. In this study, the cycle times of FAST and four alternative sheet metal forming technologies for producing an identical demonstrator U-shape component were evaluated. The different stages of each forming technology were compared and the key factors influencing the cycle time were investigated.

6.2 Study of the FAST formed U-shape components

6.2.1 Springback analysis of formed components

U-shape components are one of the representative parts in sheet metal forming and therefore a typical geometry used in sheet metal forming testing (Stanton et al., 2010; Stanton et al., 2009). In this study, the FAST forming trials of U-shape components were conducted using the dedicated pilot production line Uni-Form at a forming temperature from 300°C to 450°C and a forming speed from 100 mm/s to 380 mm/s, using the AA6082 in T4 and T6 tempers in order to identify the effects of forming temperature, forming speed and material temper on the springback behaviour of AA6082 under the FAST forming conditions.

The T4 tempered material formed at 300°C with different forming speeds are displayed in Figure 6.1. Example components formed using T4 and T6 tempered material are presented in Appendix 3.

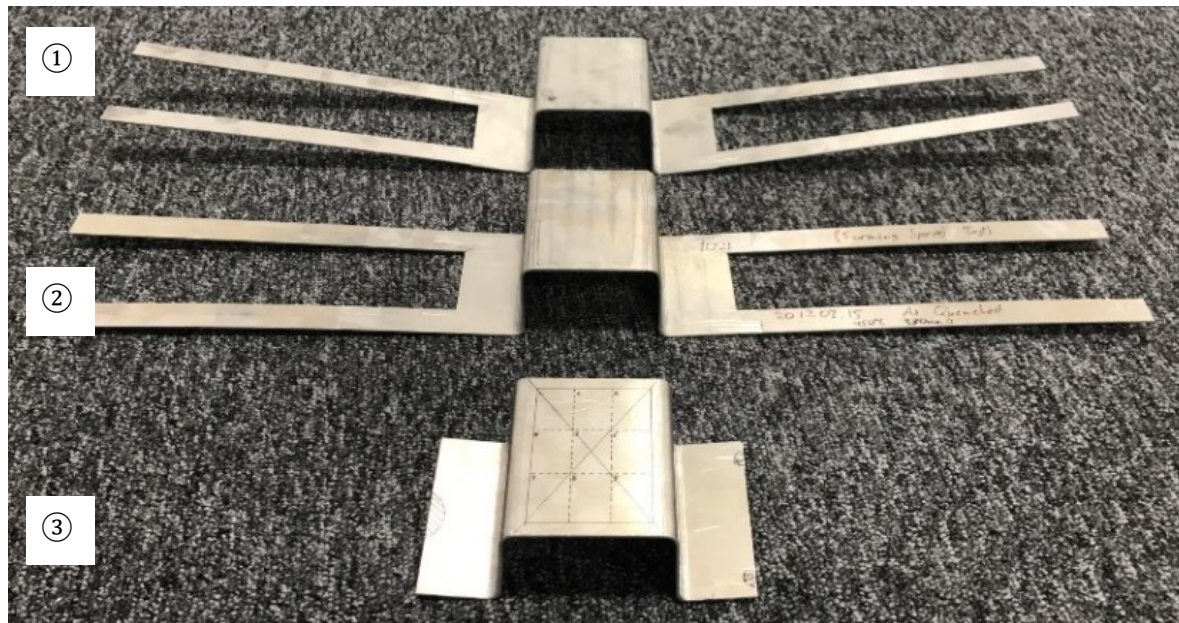


Fig 6.1 Three formed U-shape components using AA6082-T4 at different forming conditions ① 300°C, 150 mm/s; ② 300°C, 380 mm/s; ③ 300°C, 250 mm/s

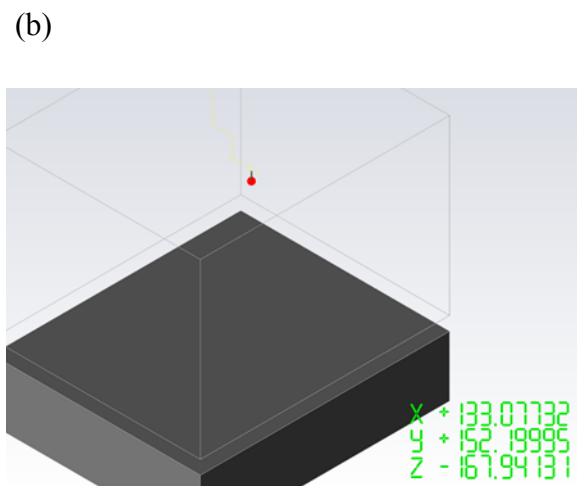
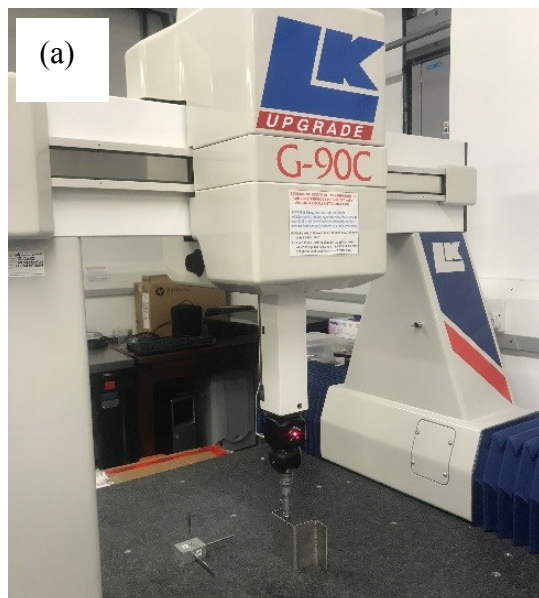


Fig 6.2 The profile measurement of the formed component using CMM (a) LK G-90C CMM machine, (b) Space coordinates obtained using the CAMIO software

The profile of the formed components was measured using the LK G-90C Coordinate Measuring Machine (CMM), as shown in Figure 6.2 (a). Five different positions on the bottom surface, two sidewalls and two flanges respectively of the component outer surface were selected and measured. The space coordinates of these positions were obtained through the dedicated software CAMIO, as shown in Figure 6.2 (b). The outer surface of the formed components were replotted in Solidworks using the coordinates and the springback angles were measured. Both the front and back profiles of the component were examined and the average springback angles were calculated.

According to the international standards on springback evaluation and previous studies on springback conducted by automakers (British Standard, 2017 (b); Bhattacharya et al., 2011 (a)), two angles were selected for describing the springback condition of the formed component, as shown in Figure 6.3. One is the flange springback θ_A and the other is sidewall springback θ_B .

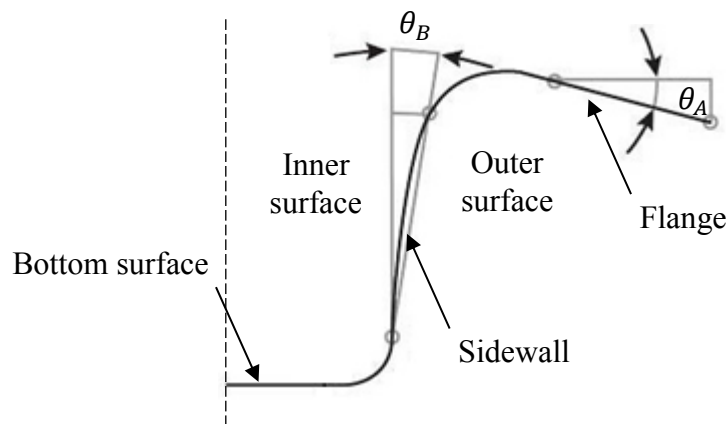


Fig 6.3 Schematic drawing of the different springback angles studied for the formed component; θ_A the flange springback and θ_B the sidewall springback

Figure 6.4 shows the effect of forming temperature on springback at a forming speed of 100 mm/s for T4 and T6 tempered alloys after the FAST process. It is clear that the both flange springback and the sidewall springback decrease with increasing the forming temperature from 300°C to 450°C and flange springback is generally larger than the sidewall springback.

For the components formed by AA6082-T4, the flange springback decreased by 48.4% from 7.54° to 3.57° and the sidewall springback reduced by 54.4% from 3.73° to 1.70°. In addition, it can be seen that the springback of T6 tempered alloy is more sensitive to the increase of the forming temperature compared to T4. The flange springback witnessed a drop by 62.6% from

10.41° to 3.89° and the sidewall springback experienced a reduction by 71.2% from 5.93° to 1.71°.

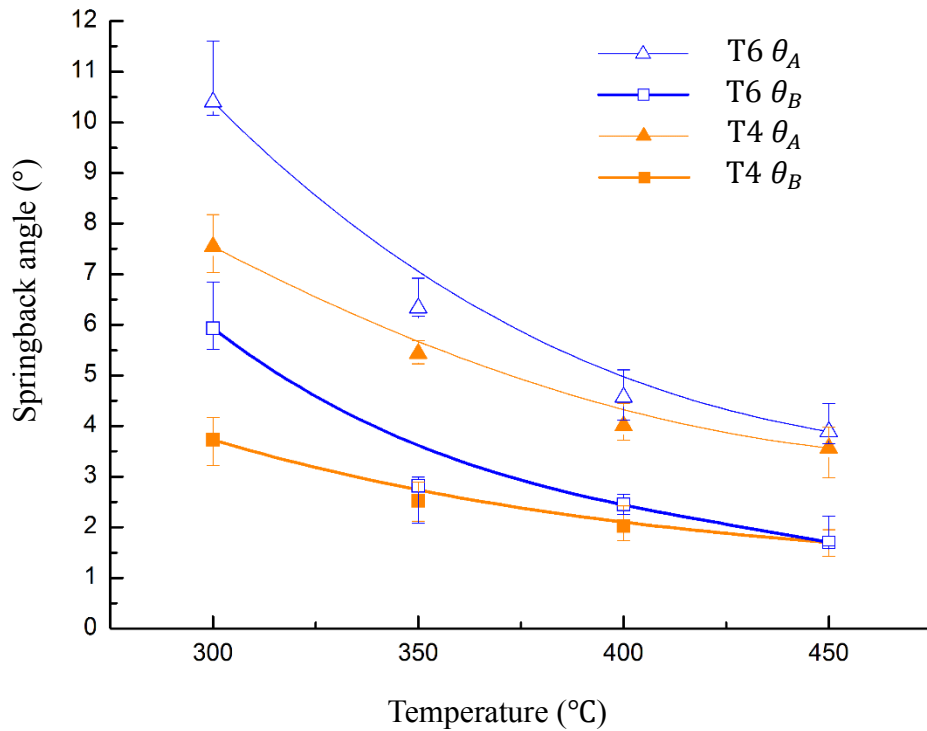


Fig 6.4 Effect of forming temperature on the springback for AA6082-T4 and T6 at a forming speed of 100 mm/s

In general, springback refers to the elastic recovery of the nonuniform residual stress in the formed component once the forming load is removed (Altan and Tekkaya, 2012(a)). The flange springback is closely related to the sidewall springback and it can be regarded as the integration of the incremental springback angles of the specific sections of the sidewall. Therefore, the flange springback is generally larger than the sidewall springback. Similar results can be found in the U-shape study of AA6xxx-T61 (Bhattacharya et al., 2011 (b); Oliveira et al., 2007).

When the forming temperature is increased, the decrease of the springback is mainly due to the material's flow behaviour at elevated temperatures. As demonstrated in Section 5.4, the yield stress of AA6082-T4 and T6 decreases with increased forming temperature. The decreased yield stress as well as lower flow stress lead to less stored elastic energy at the same strain level. Therefore, the changes of the strain due to the elastic recovery is smaller when the applied forming load is released. Meanwhile, the lower yield stress leads to lower deformation resistance. In the sections of the component where the bending deformation occurs, the ratio of

the plastic deformation is improved, which results in reduced springback angles. This can also be utilized to explain the effect of material temper on the springback of these two materials, since the AA6082 in T6 temper exhibits much greater yield stress compared to the T4 temper when the forming temperature is below 450°C. Through the springback analysis of aluminium alloys AA5082-O, AA6016-T4 and AA6111-T4, Deng et al. (2017) and Asnafi (2001) also found that the higher yield strength of the material leads to the increased springback.

In addition, both the tensile and compressive stress states of the outer and inner surfaces of the metal blank especially at the two bending corners decrease during the draw-in process with increased forming temperature, which is due to the overall stress level of the material decreasing with increasing temperature. This leads to smaller residual bending moment within the formed component after stamping. Moreover, according to the numerical study of the U-shape springback using AA5754-O, a reverse bending effect due to the tangential stress distribution on the outer and inner surfaces of the formed part could be observed with the increased forming temperature from 25°C to 250°C, which keeps the sidewall straight and reduces the flange springback (Kim et al., 2008). Similar stress distribution which showed the reverse bending effect of the aluminium U-shape component formed at elevated temperatures of 250°C can also be found in Wang et al. (2017).

It is shown in Figure 6.4 that the difference between both types of springback angles of the AA6082-T6 and T4 becomes smaller when increasing the forming temperature from 300°C to 450°C. When the forming trials were conducted at 450°C, the springback angles became almost identical for both materials. This is consistent with the difference of the flow stress of these two materials at each forming temperature, as shown in Section 5.4. The difference of ultimate tensile stress (UTS) reaches the maximum of approximately 40 MPa between the AA6082-T6 and T4 materials at 300°C, which corresponds to the maximum difference on springback of these two materials among all four forming temperatures. When the forming temperature was at 450°C, the almost identical thermo-mechanical behaviours of AA6082-T4 and T6 were observed with the same springback for the formed components.

In summary, the springback can be significantly reduced through increasing the forming temperature in the FAST process, due to the significant reduction of flow stress of the material and thus the residual bending moment within the formed component.

The effect of forming speed on the springback angles at a forming temperature of 300°C for AA6082-T4 and T6 after the FAST process is presented in Figure 6.5. It is worth mentioning that the forming speed in this study is much faster compared with other studies on springback and more representative of industrial production scenarios (Laurent et al., 2011; Naka and Yoshida, 1999). Similar to the forming temperature, the forming speed makes a significant difference on the springback angle of the formed components. In the case of AA6082-T4, the flange springback decreased by 59.7% from 7.54° at 100 mm/s to 3.04° at 380 mm/s, and a reduction of 63.3% from 3.73° to 1.37° for the sidewall springback. For the AA6082-T6, the springback angles also show a considerable fall from 10.41° to 7.21° (30.7%) and from 5.93° to 3.76° (36.6%) for the flange and sidewall springback respectively, when the forming speed was increased from 100 mm/s to 380 mm/s.

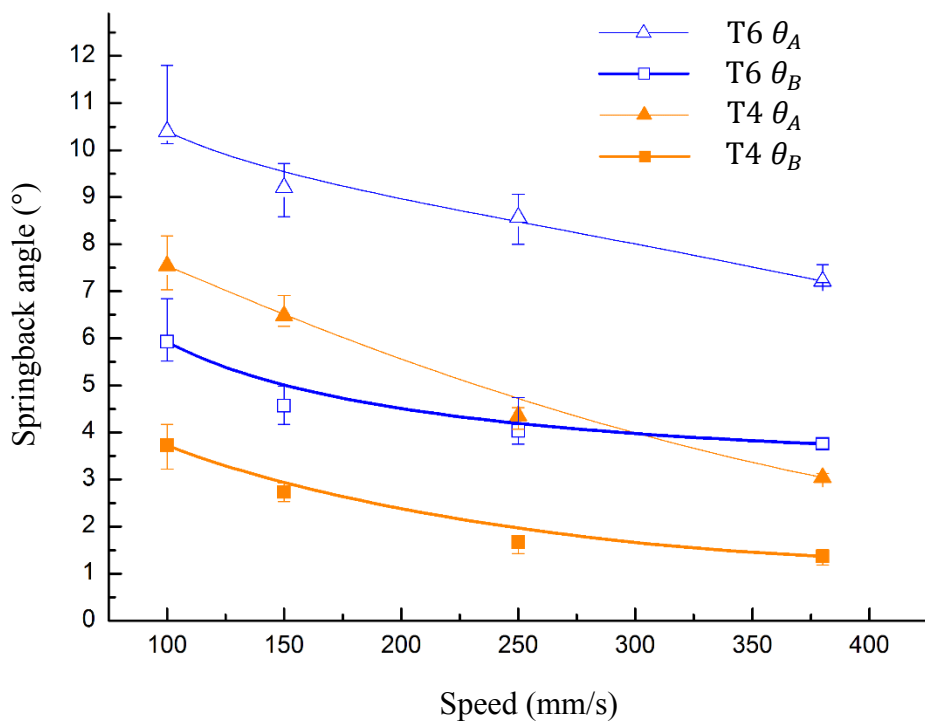


Fig 6.5 Effect of forming speed on the springback for AA6082-T4 and T6 at a forming temperature of 300°C

Generally, the springback of the T6 tempered alloy is more severe than the T4 tempered alloy in all tested forming speeds at 300°C. This is due to the higher flow stress induced by the material temper at the same forming condition and thus the higher residual bending moment as

discussed previously. According to the strain rate hardening effects, higher forming speed corresponds to larger strain rate during the deformation and leads to higher flow stress. In some studies on springback of AA5754, it was found that the increased forming speed leads to larger springback, which was the opposite of the results observed in this study (Choi and Huh, 2014; Kim et al., 2008). However, it needs to be clarified that such forming processes were conducted at isothermal conditions and within a relative low forming speed ranging from 1 mm/s to 20 mm/s. In light of the stress strain curves obtained for AA6082-T4 at different strain rates and different temperatures as shown Section 5.4, it is clear that the strain rate hardening for AA6082 is not pronounced at 300°C, which implies the strain rate hardening does not dominate the forming processes which are conducted at 300°C. The FAST forming trial is a typical non-isothermal forming process, in which the blank is hot and the forming tools are cold. Hence, it can be deduced that the change on the flow stress driven by the temperature of the specimen have the decisive effect on the springback in the FAST process. The higher forming speed significantly reduces the duration of the forming stage, which results in a higher temperature as well as lower flow stress retained by the blank from contacting the punch until fully deformed within the forming tools. Hence it can be concluded that the increased forming speed would be beneficial to restrain the springback in the FAST process within the test forming speed range at a forming temperature of 300°C.

6.2.2 Surface roughness of the formed components

The visual appearance of the formed component is an important factor of the overall product quality to the end-users, especially for the outer panel components of vehicles (Bensalah et al., 2014). Despite the anodizing, phosphating and painting processes to improve the surface finish of the formed components (European Aluminium Association, 2002 (b)), the surface roughness (Ra) of the panel components used for Class A surfaces, which are directly visible on a vehicle, should be within 0.6 μm to 1.2 μm (Chang, 2016).

In this study, the outer surface of the formed components were measured using the Wyko NT9100 Optical Profiling System, as shown in Figure 6.6. The surface was divided into nine sections as shown in Figure 6.7. For each section, at least five measurements were taken to obtain the average surface roughness. Four formed components corresponding to four different forming conditions were measured, namely FAST at 300°C using AA6082-T4 and AA6082-T6

and FAST at 450°C using these two materials. The surface roughness of the as-delivered T6 blank was also measured as the reference. In addition to the traditional surface roughness, such as Ra (British Standard, 2002), the research on three dimensions (3D) surface topography has been gradually conducted in recent years, which meets the need for giving a comprehensive description of 3D surfaces specifically for the precision machining and milling purposes (Cheng et al., 2017; British Standard, 2016 (a); British Standard, 2016 (b); Dong et al., 1994). As the dedicated measuring equipment is required (Stout and Blunt, 2000) and the evaluation the surface roughness in this study follows the requirements of automakers, the 3D surface roughness was not considered in this study.



Fig 6.6 Wyko NT9100 Optical Profiling System

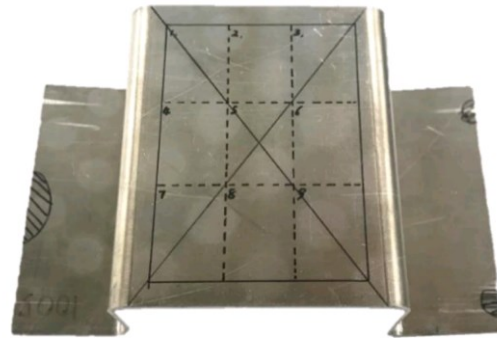


Fig 6.7 Formed component with marked outer surface for measurement

As is shown in Figure 6.8, the average surface roughness (Ra) for the as delivered AA6082-T6 blank is 487.74 nm. The surface roughness of the forming tools is around 500 nm. When the FAST process was conducted at 300°C, the surface roughness of the T4 and T6 components were 510.32 nm and 499.13 nm. These values increased to 597.88 nm and 584.5 nm respectively when the forming temperature was raised to 450°C. In general, the T6 temper material shows better surface finish compared with the T4 and the higher forming temperature results in the deterioration on the surface roughness of the formed components for both materials. According to the friction study of aluminium alloys at elevated temperatures (Holmberg and Matthews, 2009), it was found that the adhesion as well as the average coefficient of friction increased with increasing forming temperature from 25°C to 450°C (Hu

et al., 2017; Dohda et al., 2015). The surface of the blank becomes softer and more susceptible to the contact with the forming tools, which results in a rougher surface of the formed component.

In this study, the surface roughness of the FAST formed components meets the requirement of the automotive industry within 600 nm, which demonstrates the capability of FAST to maintain a proper surface finish after heating and forming. In addition, the FAST process is able to reduce the forming temperature to the minimum level required to form the components, which further facilitates a better surface finish of the formed components.

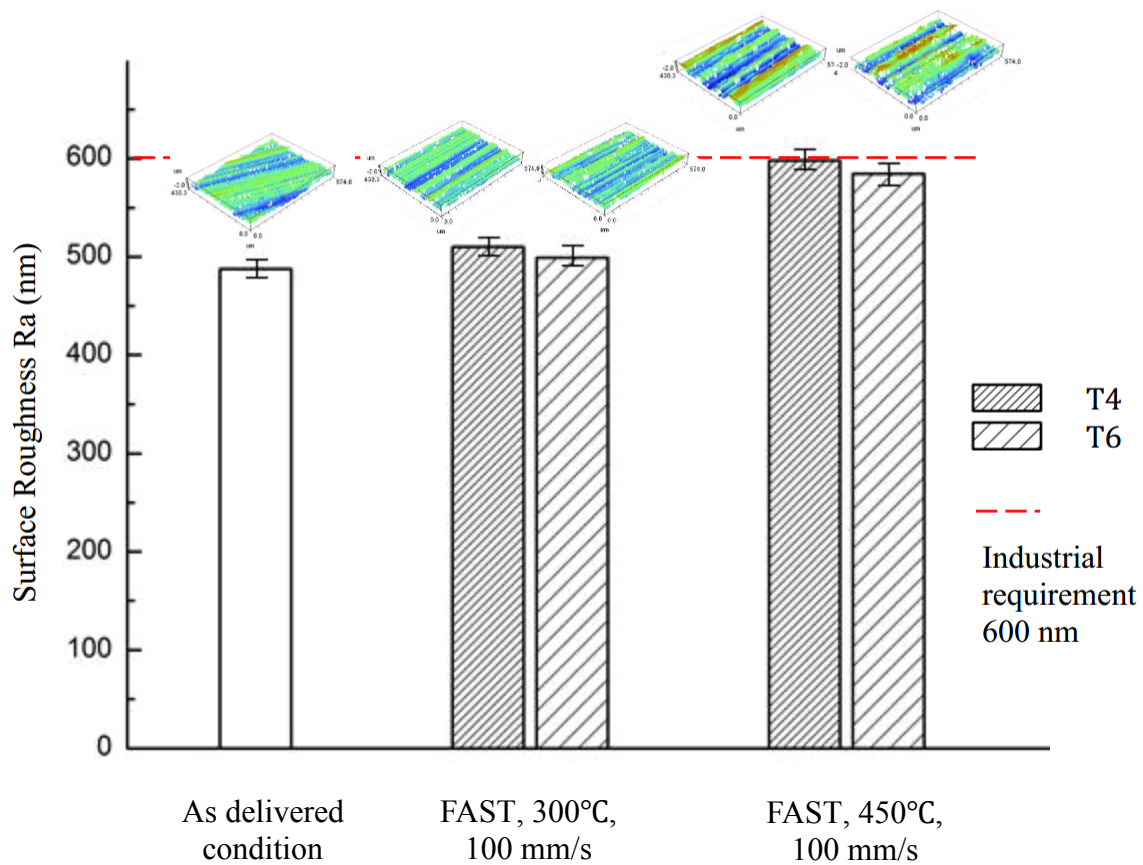


Fig 6.8 Surface roughness of the formed components top surface using AA6082-T4 and T6 at different forming conditions

6.2.3 Post-form strength study of the formed components

The formed U-shape components after in-die quenching were transferred to the incubation chamber of Uni-Form to apply the paint bake cycles, and the hardness was subsequently

measured. Three positions on the inner surface of the formed components, namely the centre of the bottom surface, the centre of the sidewall and the edge of the bottom surface were selected to provide the representative overall post-form strength of the formed components.

Figure 6.9 shows the hardness of the T4 tempered specimen formed at 450°C and 100 mm/s after paint bake treatments. The hardness of the position 1, 2 and 3 are 107.7 Hv, 105.3 Hv and 106.8 Hv respectively after P&B A and 111.3 Hv, 111.8 Hv and 112.3 Hv after P&B B. It can be found that the hardness of position 2 is slightly lower than the other two positions. This can possibly be due to the quenching rate of the sidewall being lower than the bottom surface and edge area which contacts with the dies firmly during the deformation. The diffusion controlled precipitation hardening is dependent on the quenching rate and higher quenching rate leads to better precipitation hardening response (Luan et al., 2016 (b); Milkereit et al., 2012).

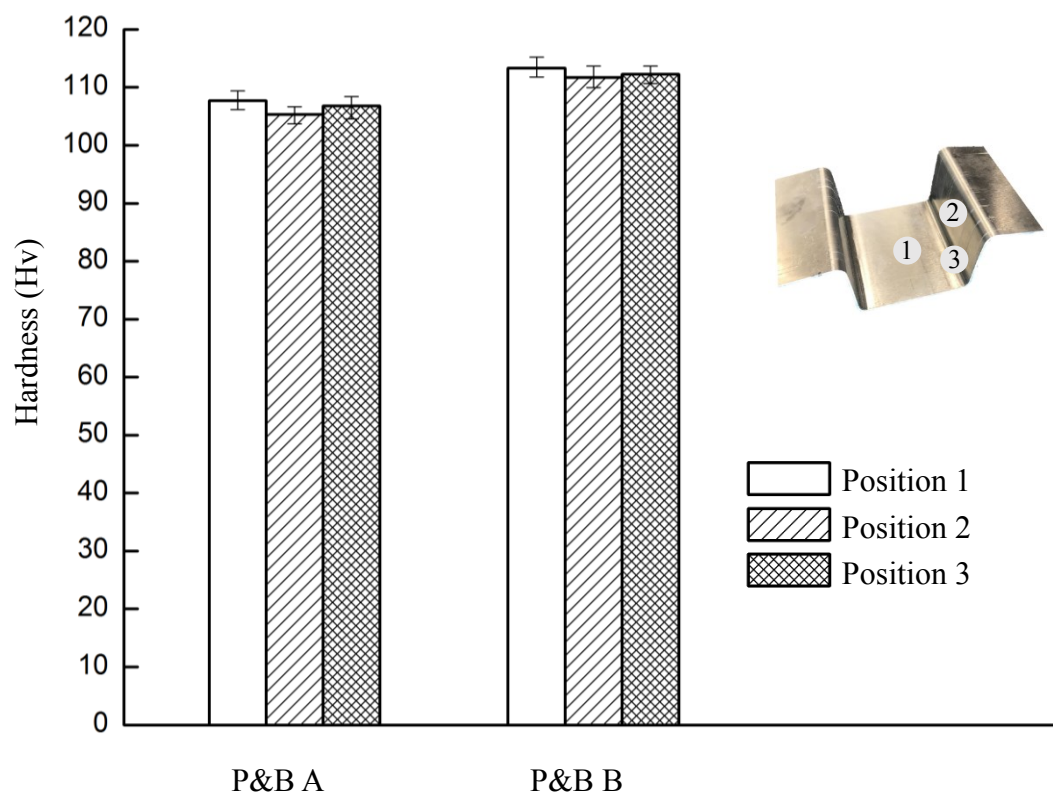


Fig 6.9 Post-form hardness of AA6082-T4 formed at 450°C 100mm/s after P&B A and P&B B

In general, the hardness of the formed components after paint bake cycles is consistent with the hardness of the samples in the FAST heat treatment tests at the same forming conditions, as

presented in Section 5.3. The post-form strength of all formed components using AA6082-T4 and T6 reaches the hardness as high as 105 Hv on different locations after P&B A and over 110 Hv after P&B B, which is more than 95% of the as-delivered T6 material strength. The hardness of the formed components after paint bake cycles was utilized to calibrate and validate a unified post-form strength prediction model, which was proposed to model the precipitation hardening behaviour of 6xxx series aluminium alloys after deformation and subsequent artificial ageing. The details can be found in the co-authored studies (Zhang et al., 2019; Zhang et al., 2018 (a)).

6.3 Benchmark study on cycle time of the FAST process and other forming technologies

The sectors most commonly employing sheet metal forming are the civil aviation and the automotive industries, especially in the manufacture of inner and outer panels of vehicles. The component requirements have become increasingly demanding in terms of achieving greater mechanical properties at lower cost and shorter cycle time (Altan and Tekkaya, 2012 (a); Altan and Tekkaya, 2012 (b)). Such a requirement is expected given how the effectiveness of producing a body-in-white (BIW) significantly affects the business performance of automakers, particularly for high volume production. For example, for the full aluminium bodied Jaguar XJ model with a production volume of more than 30,000 vehicles per year, the mass of the BIW was around 295 kg, more than 259 kg of which was made by sheet metal stamping (Hirsch, 2014). Every 10 second improvement in the cycle time would lead to a 3.47 days reduction in the total labour and machine time, with significant cost savings.

Various factors of the stamping process influence the quality of the final component and the manufacturing efficiency (Karbasian and Tekkaya, 2010). Among these factors are the forming temperature, forming speed, quenching rate, and the required post-form treatments. Research has widely been conducted to correlate these factors to the quality of the formed components (Kiliclar et al., 2016; Fan et al., 2013; Abedrabbo et al., 2006). However, the analyses of these factors on the manufacturing cycle times is still limited. Only a few studies focusing on semiconductor manufacturing and high speed milling have been conducted in the past (Monreal and Rodriguez, 2003; Akcalt et al., 2001). In this study, an evaluation of the manufacturing cycle time for producing a U-shape component was conducted. Six sheet metal forming processes including the FAST at different forming temperatures, HFQ, W-Temper, traditional warm forming and cold stamping were employed and evaluated.

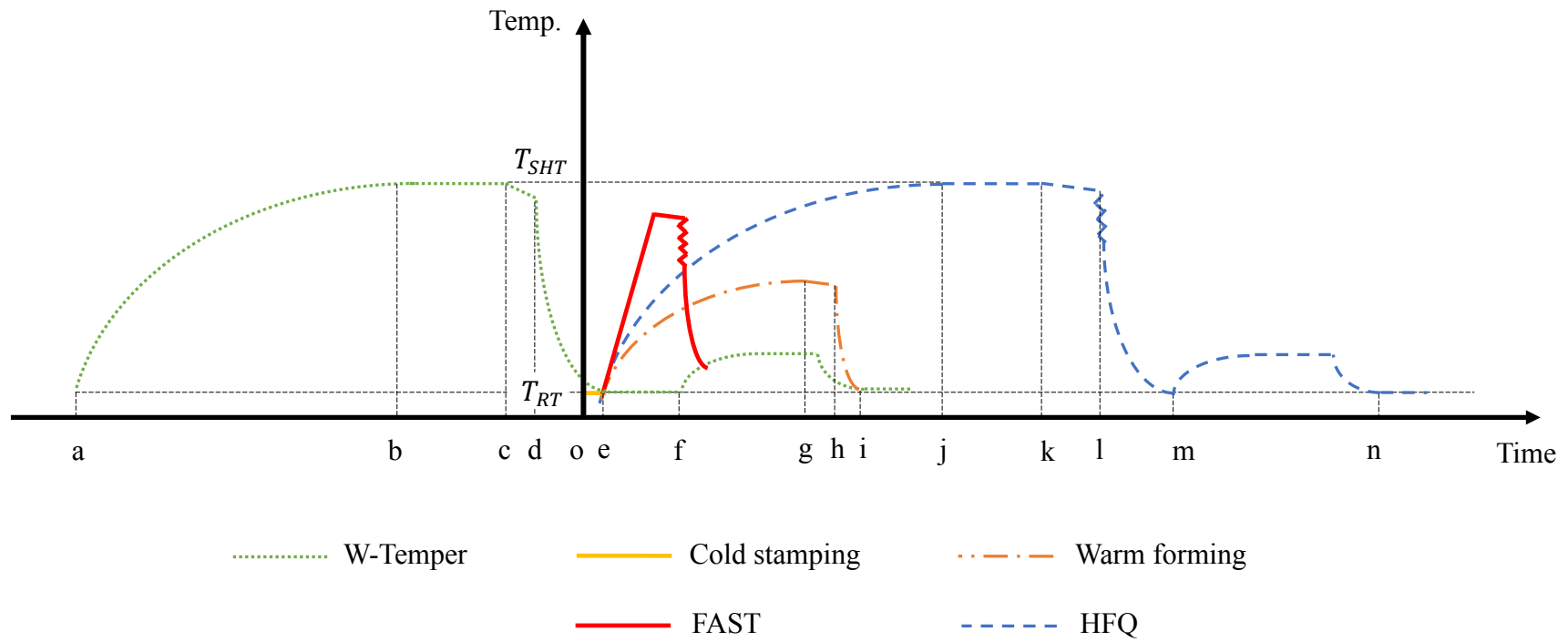


Fig 6.10 Temperature evolution and forming stages of FAST, W-Temper, HFQ, warm forming and cold stamping processes

All the forming processes were duplicated in the laboratory to produce an identical U-shape demonstrator component. The cycle time of the warm forming from literature (Harrison et al., 2013 (b)) was used as the reference. The FAST process was conducted using the Uni-Form with two forming temperatures of 300°C and 450°C. For the HFQ process, the aluminium sheet was first heated to the solution heat treatment temperature and soaked for 5 minutes in the chamber furnace, transferred to the die, and formed and quenched in a single operation. The formed piece was then held in the closed dies until fully quenched. Similar to the HFQ process, in the W-Temper process the specimen was solution heat treated, but then transferred to a quenching tank before stamping at ambient temperature. The temperature profiles of these forming processes compared with the FAST process are shown in Figure 6.10 and the forming stage description of different forming processes is demonstrated in Table 6.1.

Table 6.1 Description of forming stages of W-Temper, cold stamping, warm forming and HFQ processes

Process	Period	Stage	Nomenclature
W-Temper	a-b	Solution heat treatment (heating)	t_h
	b-c	Solution heat treatment (soaking)	
	c-d	Blank transfer	t_f
	d-e	Water quenching	
	e-f	Stamping	
	f-i	Artificial ageing	t_p
Cold stamping	o-e	Stamping	t_f
Warm forming	e-g	Blank heating	t_h
	g-h	Blank transfer	t_f
	h-i	Stamping	
HFQ	e-j	Solution heat treatment (heating)	t_h
	j-k	Solution heat treatment (soaking)	
	k-l	Blank transfer	t_f
	l-m	Stamping and in-die quenching	
	m-n	Artificial ageing	t_p

Five forming trials were conducted for each forming process and the cycle time was recorded and averaged. It should be noted that a much more comprehensive table could be drawn taking into account all the stages involved in the different processes, such as blank destacking, die and punch lubrication and the formed component cleaning, some of which are identical across all sheet metal forming processes (Swift and Booker., 2013). However, the present research is limited to those stages that, according to various studies (Neugebauer et al., 2012; Karbasian and Tekkaya, 2010), are the most significant, and have the greatest effects on the cycle time. The stage times considered in this analysis were classified as the heating time t_h , forming time t_f and post processing time t_p . The heating time represents the time required to conduct the heat treatment, the forming time is the sum of the blank transfer, die closing, forming and in-die quenching time, and the post processing time accounts for any post-form heat treatments.

Table 6.2 presents the average manufacturing cycle time for different forming processes. For confidentiality, the specific heating rate and heating times for the FAST process are not shown in the table.

Heating is the most substantial factor influencing the cycle time, with various cutting-edge equipment being developed for warm and hot stamping processes (Kolleck and Veit, 2011). As the most time consuming procedure in the forming processes at elevated temperatures, any reduction in heating time will significantly reduce the overall manufacturing cycle time. Chamber furnaces of different geometries, as shown in Section 4.3.1 and 4.4.1, were used to study the cycle time of W-Temper, warm forming and HFQ processes. The average heating rate measured was around 1°C/s, which is consistent with statistical results obtained from the current automakers using chamber furnace or tunnel furnaces. For example, the warm forming process for aluminium sheet used by Ford takes approximately 180 seconds to heat the specimen to 200°C (Harrison et al., 2013 (a)). Through utilizing contact heating with platen heaters in the FAST process, the average heating rate can be improved significantly from 1°C/s to nearly 200°C/s, reducing the heating time from more than 500 seconds to less than 2.5 seconds. This suggests that the heating process is an area where substantial improvements can be made in terms of increasing the production efficiency. Moreover, the solution heat treatment is not compulsory in the FAST process and soaking of the metal blank for 300 seconds is no longer needed, which reduces the target heating temperature and the required heating time.

Table 6.2 Cycle time and specifications of the six forming processes for producing the U-shape components

No.	Forming Tech	Material	Forming Temp (°C)	Forming Speed (mm/s)	Ave heating rate (°C/s)	Cycle time			
						Heating time (s)	Forming Time (s)	Post Proc. Time (s)	Total time (s)
1	FAST	AA6082-T6	300	250	~200	< 2	5.7	None	<7.5
2	FAST	AA6082-T4	450	250	~200	< 2.5	6.2	None	<8.5
3	W-Temper	AA6082-T6	25	250	~1	525+300	16.5	t_{agieng}	$841.5+t_{agieng}$
4	Cold stamping	AA6082-T4	25	250	NA	NA	4.4	None	4.4
5	Warm forming	AA6082-T6	200	N/A	~1	180	15	None	195
6	HFQ	AA6082-T6	535	250	~1	525+300	14.4	t_{agieng}	$839.4+t_{ageing}$

As reported by Karbasian and Kollack (Karbasian and Tekkaya, 2010; Kollack and Veit, 2011), the cycle time of hot stamping processes mainly lies on the furnace residence time and the die closing time. In industrial production using warm forming, the time from the moment the blank exits the furnace to the end of the forming operation is approximately 15 seconds (Harrison et al., 2013 (b)). The forming time of FAST was 5.7 seconds and 6.2 seconds for forming temperature of 300°C and 450°C respectively. As the formed components were only held and quenched to the paint bake temperature 180°C, it took 0.5 seconds longer under the forming condition at 450°C. The HFQ process requires more time to fully quench the aluminium blank in the closed dies, which leads to a higher forming time compared with FAST. In the W-Temper process, the forming is conducted at room temperature without subsequent holding, although the metal blank needs to be transferred twice, namely from the furnace to the quenching tank and to the press, resulting in a total forming time of 16.5 seconds. The duration of the forming time is highly dependent on the forming process specifications and times of transfer between different forming stages. The FAST process is able to achieve a forming time of only 1.8 seconds longer than cold stamping. The forming times for the other forming processes in which a conventional chamber furnace and solution heat treatment are involved are almost the same, ranging from 14.4 s (HFQ) to 16.5 s (W-Temper process).

The distinct feature of FAST is that the microstructure and strength of the metal blank are maintained at elevated temperatures, compared with the HFQ and W-Temper processes where the precipitates are extensively dissolved prior to stamping in order to improve the formability. The subsequent artificial ageing process usually takes as long as 8 hours (Cox, 2019) to improve the post-form strength, while the FAST and cold stamping processes do not require additional post-form artificial ageing processes. The formed components can be directly used in welding assembly and paint bake cycles. Hence, a separate furnace for post-form artificial ageing is not required in OEMs, which could lead to tremendous reduction in cycle time and manufacturing costs.

A shorter cycle time results in higher productivity, efficiency and lower energy consumption. Tier 1 suppliers and OEMs exercise strict control over the cycle time and make continuous efforts to reduce it to remain competitive. In this study, it was found that improvement on the heating process has the most significant effect on cycle time reduction. The elimination of an additional post-form ageing process also reduces the cycle time of the FAST process. Since the

ultra-fast heating rate can be achieved through the proprietary conductive platen heaters and the solution heat treatment as well as the post-form artificial ageing is not required, FAST can maintain the cycle time within 8.5 seconds, which is only 4.31% of the time of the warm forming process that is currently utilized in the automotive industry.

6.4 Summary

In this chapter, the forming trials of the FAST process using the dedicated pilot production line Uni-Form are presented. Through forming a representative geometry U-shape component from the AA6082 in T4 and T6 tempers, it is found that the springback can be significantly reduced by increasing the forming temperature from 300°C to 450°C and increasing forming speed from 100 m/s to 380 m/s. When the forming temperature is 450°C, the flange and sidewall springback can be reduced to approximately 3.7° and 1.7° respectively for both materials. This is mainly due to the flow stress especially the yield stress that reduces with increased forming temperature, which leads to a smaller residual bending moment in the formed components. The surface roughness of the FAST formed components from AA6082-T4 and T6 at different forming temperatures is generally lower than 600 nm, which meets the requirement of the vehicle body-in-white in the automotive industry. In addition, the post-form strength of all FAST formed components shows that a hardness as high as 110 Hv, which is more than 95% of the as-delivered T6 tempered material can be achieved after the application of paint bake cycles. Furthermore, the benchmark study of the manufacturing cycle time reveals that the heating method strongly determines the overall manufacturing cycle time of the sheet metal forming processes at elevated temperatures. Through the ultra-fast heating and the precision processing parameters control, the FAST process can be performed in less than 8.5 seconds, which is only 4.31% of the time of the warm forming process currently utilized in the automotive industry.

Chapter 7

Conclusions and suggestions for future work

7.1 Conclusions

This study presents the development of an innovative sheet metal forming technology Fast light Alloy Stamping Technology (FAST) utilizing the heat treatable aluminium alloy AA6082 in different tempers. Different aspects of this new forming technology, including the introduction of the concept, the influence of forming temperature and material temper, and the thermo-mechanical behaviour of the alloy were investigated and compared to traditional forming technologies. The effect of ultra-fast heating rate and slow heating rate on the material properties during the heating, forming and post-form heat treatment processes are thoroughly studied. A pilot production line Uni-Form dedicated to the FAST process which realized the ultra-fast heating and precision processing parameters control was designed and fabricated as part of this study. Laboratory scale forming trials using FAST were conducted on Uni-Form, and the properties of the formed components were analysed. The key findings of this study are summarized as follows:

7.1.1 Fast light Alloy Stamping Technology (FAST) and the mechanism of ultra-fast heating on the AA6082-T4 and T6 during the FAST process

A novel sheet metal forming technology, Fast light Alloy Stamping Technology (FAST) was proposed, verified and extensively investigated in this study. In this process, the material is directly heated to the specific temperature at which the formability of the blank is sufficient to form the component with an ultra-fast heating rate over 100°C/s in order to minimize the detrimental microstructure evolutions during the heating and stamping stages and achieve the desired post-form strength with only paint bake cycles instead of post-form artificial ageing process.

Heat treatment tests following the FAST process were conducted on the naturally aged T4 and artificially aged T6 tempers AA6082 at the target forming temperatures between 300°C and

450°C. The paint bake cycles of two vehicle manufacturers were applied on the samples after the FAST process to evaluate the material properties following the industry accepted treatment processes. The experimental results have revealed that the post-form strength of the formed and paint baked component is generally more than 90% (105 Hv) and in some cases over 95% (110 Hv) of the as-delivered T6 temper (116 ± 2 Hv) blank without other post-form heat treatments.

For the T4 tempered material, the FAST process mainly dissolves the natural ageing clusters and generates the pre- β'' phase during the ultra-fast heating, facilitating the precipitation hardening response of the material. For the T6 tempered material, the microstructure evolutions involve several distinct reactions such as the phase formation, dissolution and alteration of number density simultaneously. The initial microstructure of the material contains plenty of metastable hardening phase β'' and the target temperature of the FAST process is between the normal ageing temperature and the solution heat treatment temperature. When the forming temperature is close to 300°C, a portion of the pre-existing hardening phase β'' remains and a portion of the precipitates coarsen. The ultra-fast heating rate significantly shortens the heating time and minimizes the coarsening. When the forming temperature is increased to 450°C, the dissolution of the precipitates dominates the evolution of the microstructure. As the exposure of the material to elevated temperatures is minimised, full strength of the material can be regained through the paint bake cycles due to the minimal formation of the stable β phase in the microstructure. In addition, the TEM scans of samples for specimens after the FAST process prove that the majority of β'' phase, the dominant hardening phase of Al-Mg-Si alloys, seldom coarsen after heating and forming, and distribute extensively within the microstructure after the paint bake cycles.

Uniaxial tensile tests under the ultra-fast heating condition have been performed for both materials in this study. Through heating the metal blank to an elevated temperature, FAST provides a much lower flow stress during deformation and a larger elongation to failure compared with traditional cold stamping. When FAST is conducted at 300°C, the true fracture strain is over 0.50 and 0.32 for the AA6082-T4 and T6 with the ultimate tensile strength of 133.1 MPa and 180.4 MPa respectively. When the FAST is conducted at 450°C, the true fracture strain is increased to 0.85 for both materials and the ultimate tensile strength is 48 MPa.

7.1.2 The effects of slow heating rate in the forming technologies for the heat treatable aluminium alloys

While the FAST process implements ultra-fast heating, the existing warm and hot stamping processes generally employ furnace heating or heated forming tools where a much lower average heating rate of approximately 1°C/s is applied. According to the heat treatment tests, it has been found that either AA6082-T4 or AA6082-T6 samples once heated under a low heating rate of approximately 1°C/s to temperatures between 300°C and 450°C, a post-form strength greater than 90 Hv is difficult to achieve through subsequent paint bake cycles or artificial ageing treatment. Instead, only 58.1% to 76.9% of the material full strength can be recovered for the AA6082-T4 and T6 under such forming conditions.

The reason for such degradation in strength is due to the low heating rate that leads to a prolonged heating time and exposes the heat treatable aluminium alloys to unfavorable elevated temperatures such as 300°C to 450°C for an excessive duration (more than 300 seconds). Precipitate coarsening becomes severe and the over-sized precipitates could not be dissolved within this temperature range, which extensively consumes the solute atoms in the aluminium matrix and is detrimental to the precipitation hardening of the material during the post-form heat treatment. This demonstrates the advantages of ultra-fast heating rate of FAST and the reason why warm forming of aluminium alloys is generally performed at forming temperatures below 250°C and the solution heat treatment is compulsory in some hot stamping processes for aluminium alloys. Since the heating rate is determined by the applied heating method, the heating schemes which are capable of ultra-fast heating rates such as contact heating and resistance heating are more beneficial to the post-form strength of the heat treatable aluminium alloys formed at elevated temperatures.

7.1.3 Dedicated pilot production line: Uni-Form

Based on the successfully validated FAST process, a dedicated pilot production line Uni-Form has been designed and fabricated to perform the forming experiments. In the design of this test facility, several schemes were considered and evaluated especially for realizing the ultra-fast heating and automated operation. Contact heating and belt conveyor were selected in light of the heating efficiency and ease of implementation on the pilot production line.

Uni-Form is comprised of four main subsystems, including a pair of proprietary conductive platen heaters, a precisely adjustable belt conveyor for transferring the specimen, interchangeable forming tools and an incubation chamber capable of various pre- and post-form heat treatments. The system is mounted on a hydraulic press with a gas spring cushion system positioned on the machine bed, which provides an adjustable stamping force. This test facility has the capability of providing an ultra-fast heating rate of up to around 200°C/s and a forming temperature up to 650°C. The temperature uniformity of the heating system varies by only 5% between the centre and the edge of the platen heater. The time control accuracy is as high as 0.1 seconds and the positioning error is within 1 mm. The Uni-Form is controlled by a microchip PIC4331. The forming parameters including the forming temperature, forming speed, transfer time and post-form heat treatments are programmed in advance and the forming trials can be conducted in a fully automated manner. As a ready-to-deploy pilot production line that has been verified through daily laboratory usage, this invention has enormous potential and could be scaled up directly to a real production line for conducting sheet material forming processes.

7.1.4 FAST forming trials and the formed components

The forming trials of the FAST process were conducted using the dedicated pilot production line to study the effects of material temper, forming temperature and forming speed on the properties of formed components. A U-shape component was selected as the demonstrator geometry to be formed.

It is found that the springback can be significantly reduced by increasing the forming temperature from 300°C to 450°C and forming speed from 100 mm/s to 380 mm/s in the FAST process. When the forming temperature is 450°C, the flange and sidewall springback can be reduced to approximately 3.7° and 1.7° respectively for both AA6082-T4 and T6. This is mainly due to the reduction in yield stress and flow stress, and a lower residual bending moment in the formed components with increased forming temperature. The surface roughness of the formed components from both materials at different forming temperatures of 300°C and 450°C is generally within 600 nm, which meets the requirement of the vehicle body-in-white in the automotive industry. In addition, an overall post-form strength as high as 110 Hv, which is more than 95% of the as-delivered T6 temper blank can be achieved after the application of paint bake cycles.

Furthermore, a benchmark study on the manufacturing cycle time has been conducted to produce the identical U-shape component using five sheet metal forming processes including FAST, W-Temper, cold stamping, warm forming and HFQ. It is found that FAST is able to maintain the manufacturing cycle time within 8.5 seconds from original blank to the formed component, which is only 4.31% of the time of the warm forming process currently utilized by automakers.

7.2 Suggestions for future work

7.2.1 Integration of cryogenic treatment into FAST

Different from forming an aluminium blank at elevated temperatures in the warm and hot stamping processes, cryogenic forming or cryogenic treatment is another approach to improve the formability of aluminium alloys. The metal blank is chilled to cryogenic temperatures at -180°C by soaking in liquid nitrogen and subsequently stamping. It has been found that the dislocation density experiences a significant increase due to the suppressed recovery at cryogenic temperatures, which result in larger elongation to failure in uniaxial tensile test and higher strain to failure in formability tests (Lee and Lin, 2016; Park et al., 2011). In addition, the influence of the Portevin-Le Chatelier (PLC) effect is avoided through the cryogenic treatment. Both uniform elongation and fracture elongation can be improved (Schneider et al., 2013; Vanhove et al., 2011).

Since FAST is able to retain the material initial microstructure and promote the ductility of the material at elevated temperatures and the cryogenic treatment is capable of optimising the material's microstructure leading to better ductility, a further improvement on ductility and formability of the heat treatable aluminium alloys is expected. Moreover, considering the incubation chamber of the Uni-Form can be converted into a freezer through connecting with a liquid nitrogen tank, the tests could be conducted in a fully automated way.

7.2.2 Further investigation of the heat treatable aluminium alloys in TX temper applied in the FAST process

Traditional material tempers used in the sheet metal forming processes include naturally aged T4 temper and artificially aged T6 temper. The newly proposed TX temper is a flexible material temper, which is produced through pre-artificial ageing of the material to different levels.

Alloys with various initial strength can be obtained. Since FAST is able to conserve the initial material microstructure and maintain its strength after the heating and forming, the difference of the initial strength results in different levels of formability and requirements on the post-form heat treatment/paint bake cycles to regain the full strength. In other words, the aluminium sheet can be tailor produced according to complexity of the designated component and the existing paint bake cycles of different vehicle manufacturers. The full strength could be regained by making the most of the existing paint bake cycles, saving time and cost for both material manufacturers and press shops.

The TX temper provides extra flexibility on forming parameter selection in addition to the forming temperature in the FAST process. However, the temper effects would gradually be diminished with the increased forming temperature from 300°C to 450°C. The cumulative effect of the forming temperature and the material temper on the material formability and paint bake response can be further explored in future studies. The temper effect can also be incorporated into the material flow behaviour modelling in addition to the effects of forming temperature and strain rate.

7.2.3 Standardization of the formability test for the heat treatable aluminium alloys at elevated forming temperature

According to this study, it has been found that the heating process i.e. the heating rate and the heating time, make a great difference on the material strength of heat treatable aluminium alloys. The microstructure of the material undergoes obvious alterations at elevated temperatures within the range of 300°C and 450°C even for a few seconds. This results in significant changes to the ductility and formability of the material at elevated forming temperatures. However, the current formability studies for the heat treatable aluminium alloys mainly concentrate on the influence of forming temperature and forming speed. The effects of heating rate and heating time are sometimes not considered, which leads to inaccurate formability data. Hence, there is an urgent need to standardize the formability tests for the heat treatable aluminium alloys at elevated forming temperatures. The heating rate, heating time and material temper should be clearly defined for these standards. For the FAST process, the forming tools of the Uni-Form can be re-designed and the formability of AA6082-T4, AA6082-T6 and AA6082-TX under ultra-fast heating conditions could be obtained.

7.2.4 Life cycle assessment (LCA) of the FAST process

Life cycle assessment (LCA) is a methodology which has come to the fore in recent years and is widely applied to systematically evaluate the impact of a process or a product to the environment (Raugei et al., 2015). In general, it takes all stages of a process or product's full life from raw material to final disposal into consideration, and presents values in terms of cumulative prime energy demand (in MJ), Global warming potential (in kg, CO_2), and acidification potential (in kg, SO_2) through the specific assessment processes. Similar to the cycle time, LCA is another key indicator of a process or product to support the business strategy or product declarations. Therefore, an LCA should be conducted for the FAST process. It can be expected that the FAST leads to energy savings and a more environmentally friendly process and provides a net positive contribution to the reduction of the car industry's environmental impact.

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Appendix

Appendix 1 Uni-Form related information

Appendix 1(a) The middle plate of Uni-Form supported by four gas springs

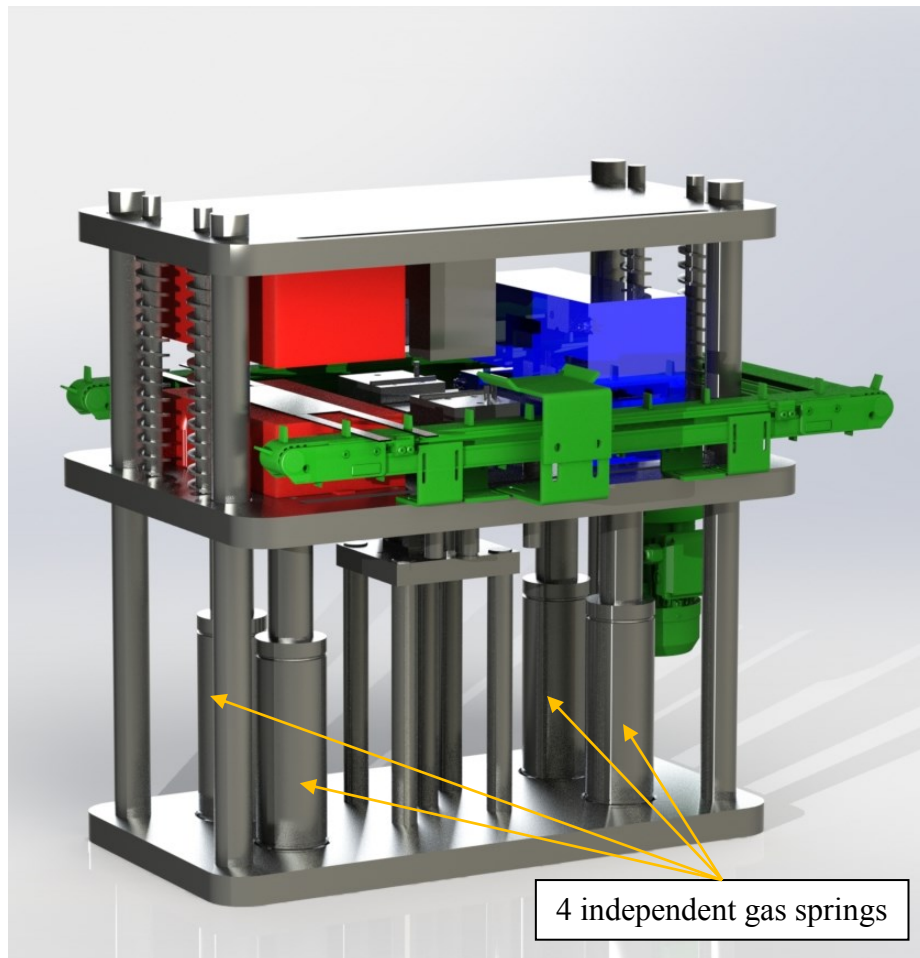


Fig. A1 Layout of Uni-Form with direct gas spring support

Appendix 1(b) The Fujifilm Prescale pressure test paper

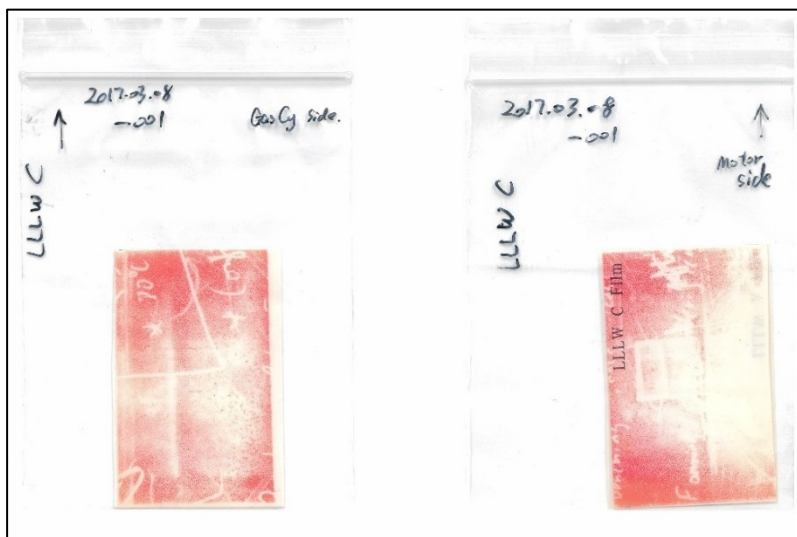


Figure A2
Pressure test paper
LLLWC

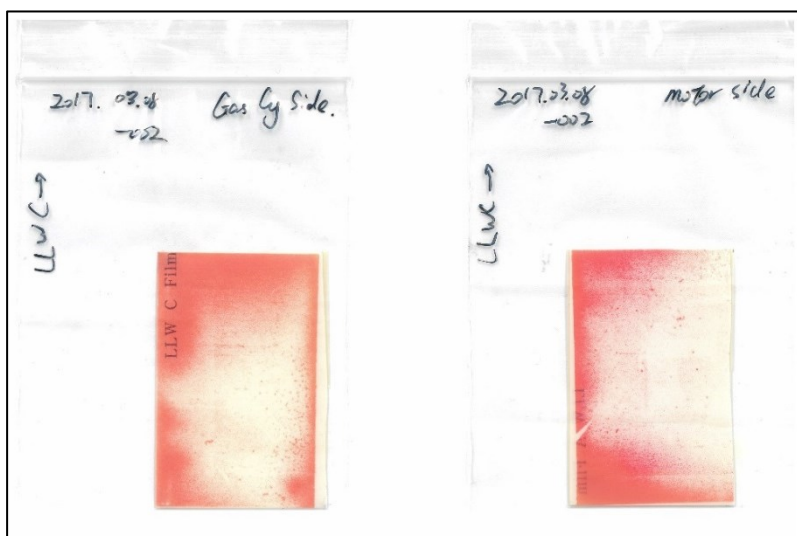


Figure A3
Pressure test paper
LLWC

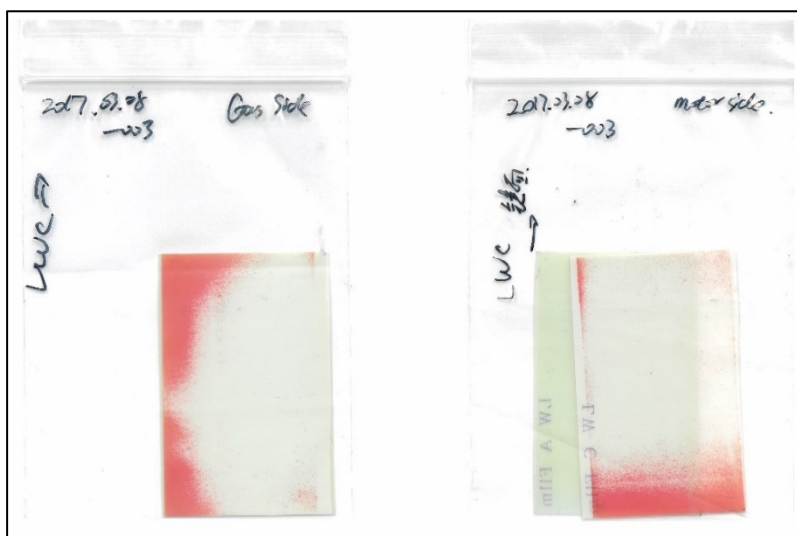
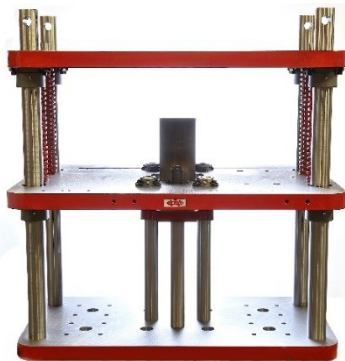
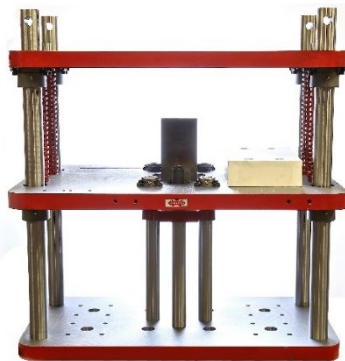


Figure A4
Pressure test paper
LWC

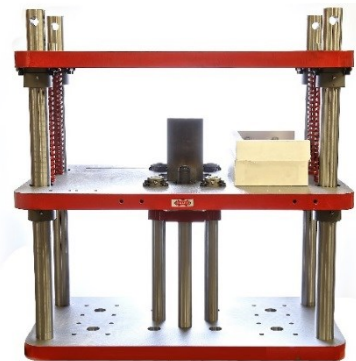
Appendix 1(c) Assembly and installation of Uni-Form



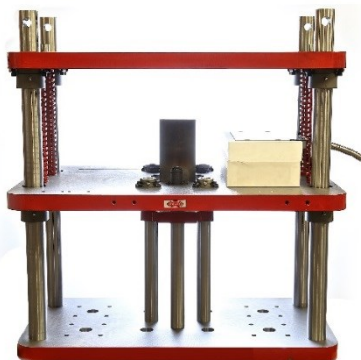
Step 1



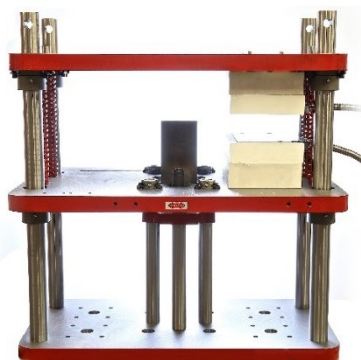
Step 2



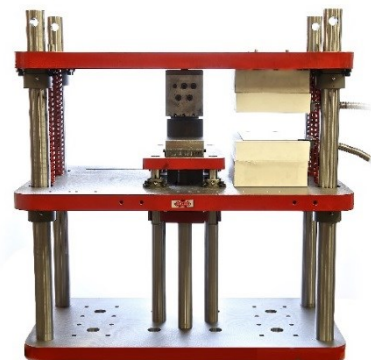
Step 3



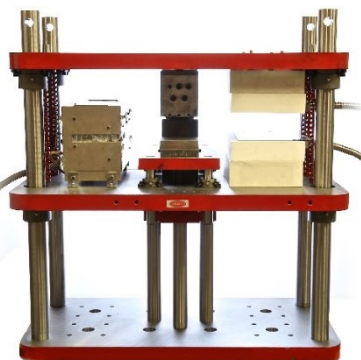
Step 4



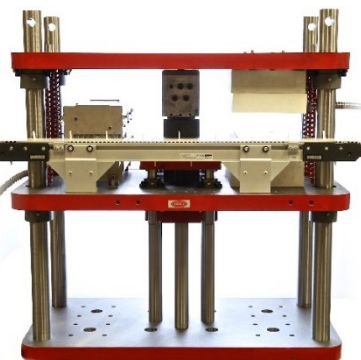
Step 5



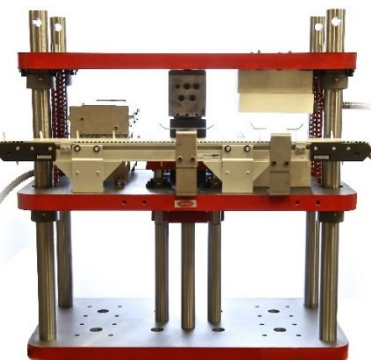
Step 6



Step 7



Step 8



Step 9

Figure A5 The assembly of Uni-Form

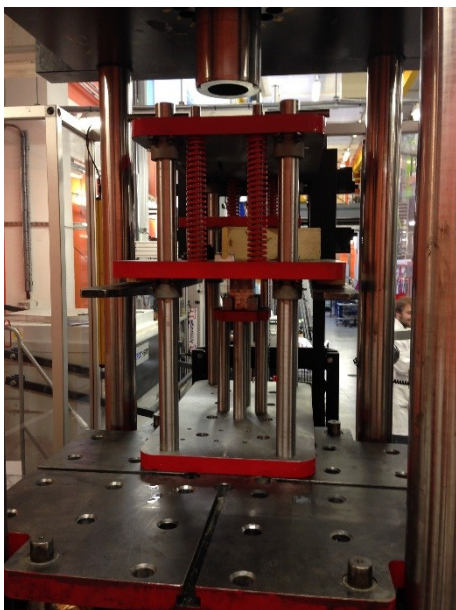


Figure A6 The installation of Uni-Form

Appendix 1(d) Pins layout of the microcontroller

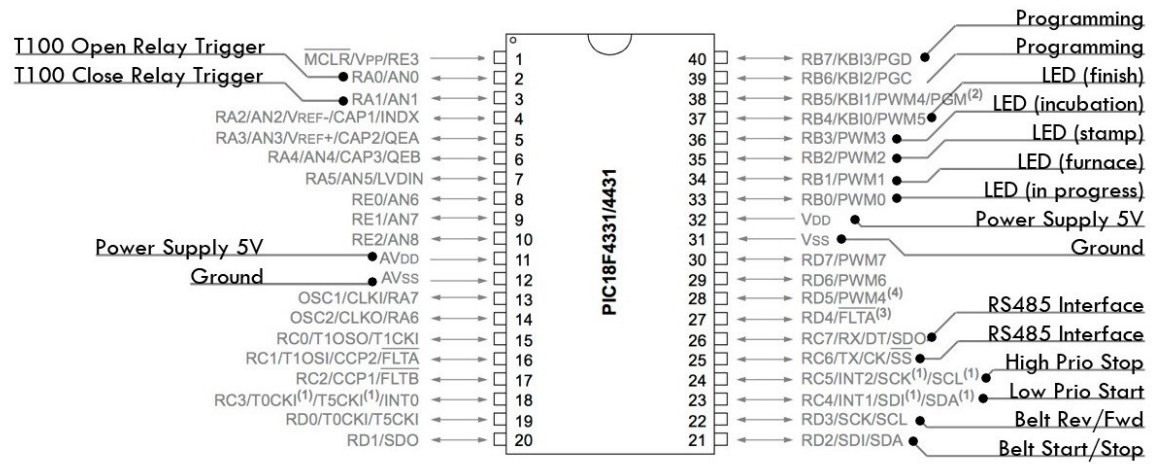


Figure A7 Microcontroller PIC4331 pin arrangement

Appendix 1(e) Relationship between gas spring cushion charged pressure and the corresponding forces within Uni-Form

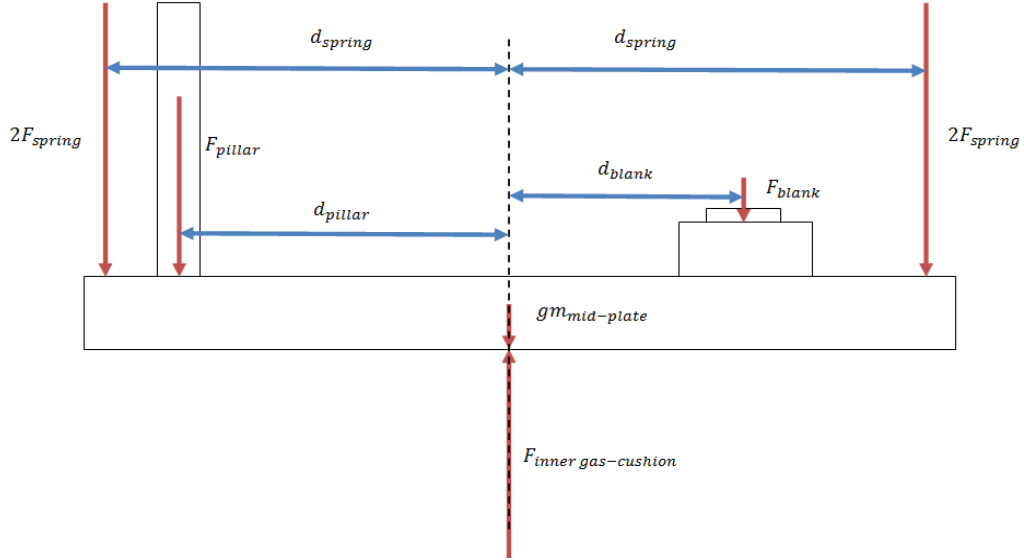


Figure A8 Force analysis of Uni-Form (the heating stage)

$$F_{pillar} + F_{blank} = F_{inner\ gas\ cushion} - gm_{mid\ plate} - 4F_{spring} \quad (\text{Eq. A1})$$

$$F_{pillar}d_{pillar} = F_{blank}d_{blank} \quad (\text{Eq. A2})$$

$$F_{pillar} = F_{blank} \frac{d_{blank}}{d_{pillar}} \quad (\text{Eq. A3})$$

$$F_{blank} \left(1 + \frac{d_{blank}}{d_{pillar}} \right) = F_{inner\ gas\ cushion} - gm_{mid\ plate} - 4F_{spring} \quad (\text{Eq. A4})$$

$$P_{heat} = \frac{F_{inner\ gas\ cushion} - gm_{mid\ plate} - 4F_{spring}}{A_{blank\ heat} \left(1 + \frac{d_{blank}}{d_{pillar}} \right)} \quad (\text{Eq. A5})$$

After calculation, the relation between gas spring cushion charged pressure and contact heating pressure can be plotted in Figure A9. Similarly the relationship between forming pressures and the gas spring cushion charged pressure can be found in Figure A10.

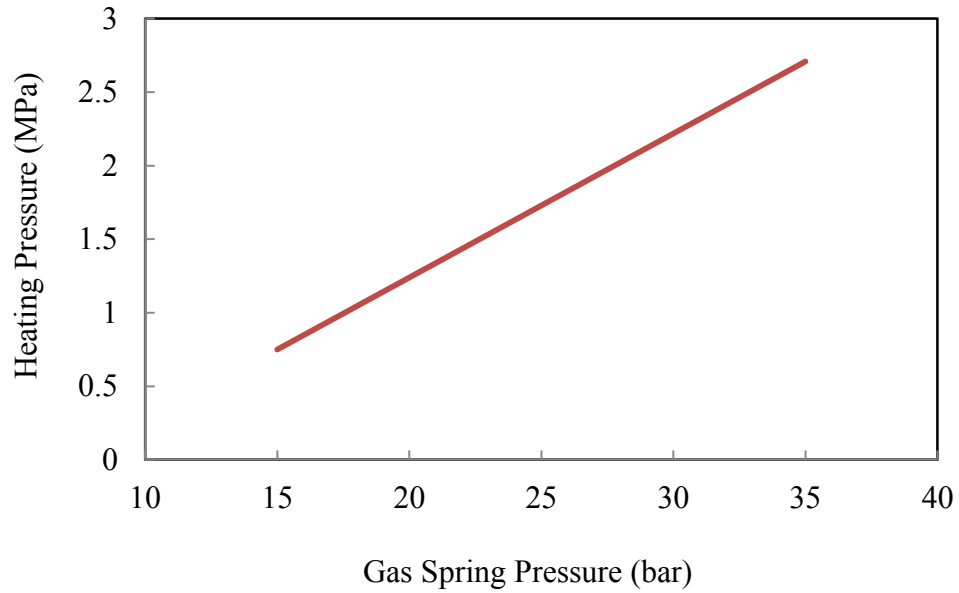


Figure A9 The relationship between the heating pressure and the gas spring cushion charged pressure of Uni-Form

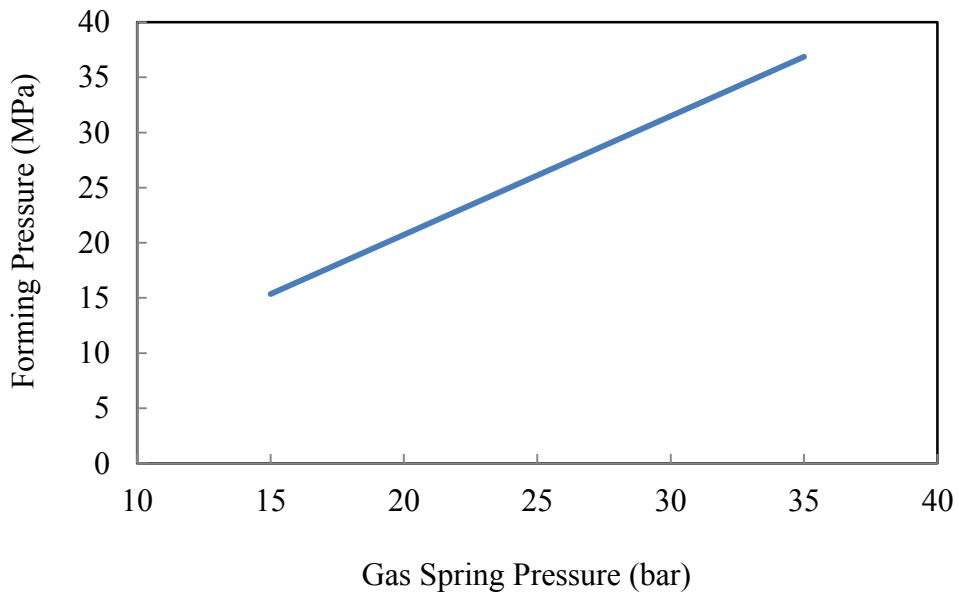


Figure A10 The relationship between the forming pressure and the gas spring cushion charged pressure of Uni-Form

Appendix 1(f) Heating rate of chamber furnace

Table A1 Heating time
(Furnace 300°C and target temp. 300°C)

Par. No.	Time (s)	Heating Rate (°C/s)
1	652	0.46
2	621	0.48
3	626	0.48
4	648	0.46
5	630	0.48
AVE	635.4	0.47

Table A2 Heating time
(Furnace 350°C and target temp. 350°C)

Par. No.	Time (s)	Heating Rate (°C/s)
1	460	0.76
2	431	0.81
3	488	0.72
4	476	0.74
5	442	0.79
AVE	459.4	0.76

Table A3 Heating time
(Furnace 350°C and target temp. 300°C)

Par. No.	Time (s)	Heating Rate (°C/s)
1	126	2.38
2	129	2.33
3	128	2.34
4	150	2.00
5	143	2.10
AVE	135.2	2.23

Table A4 Heating time
(Furnace 450°C and target temp. 450°C)

Par. No.	Time (s)	Heating Rate (°C/s)
1	463	0.86
2	446	0.90
3	460	0.87
4	475	0.84
5	488	0.82
AVE	466.4	0.86

Table A5 Heating time
(Furnace 400°C and target temp. 400°C)

Par. No.	Time (s)	Heating Rate (°C/s)
1	490	0.92
2	511	0.88
3	482	0.93
4	500	0.90
5	488	0.92
AVE	494.2	0.91

Table A6 Heating time
(Furnace 525°C and target temp. 525°C)

Par. No.	Time (s)	Heating Rate (°C/s)
1	490	1.07
2	478	1.10
3	474	1.11
4	472	1.11
5	483	1.09
AVE	479.6	1.09

Appendix 2 Flow stress of AA6082-T6 and T4 at room temperature

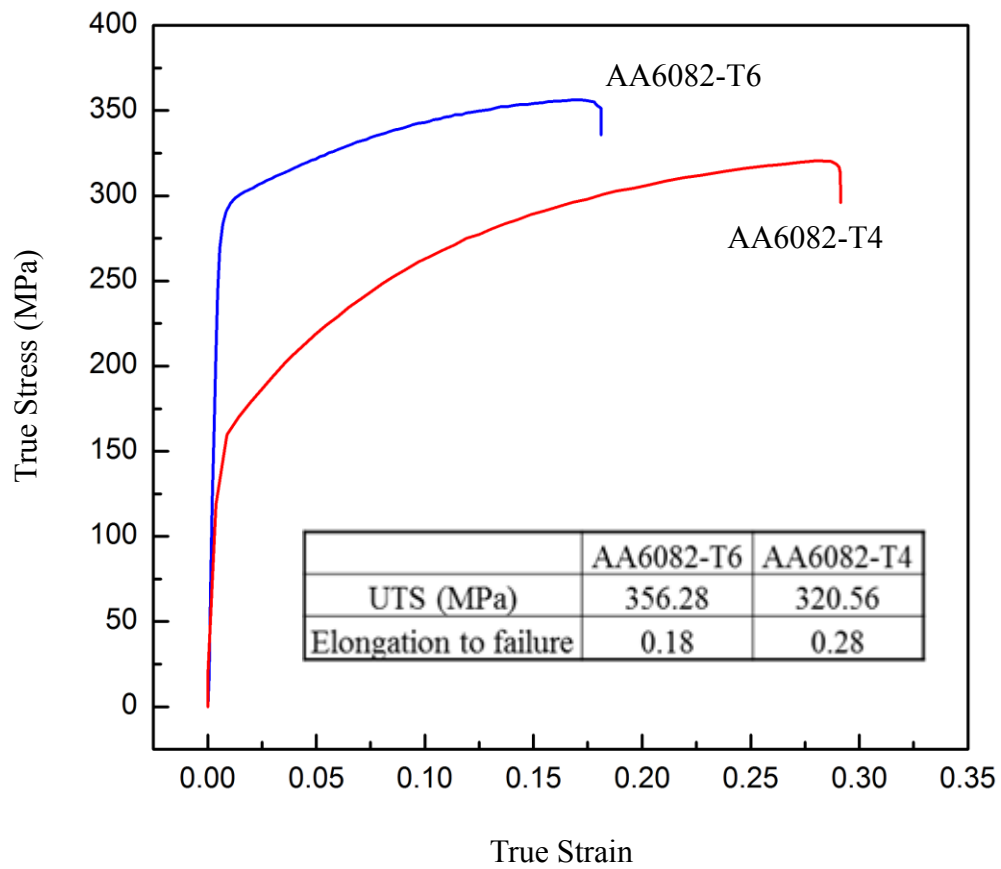


Fig A11 Stress-strain curves of AA6082-T4 and T6 at room temperature

Appendix 3 U-shape components formed by FAST using Uni-Form

Appendix 3(a) U-shape components for temperature test

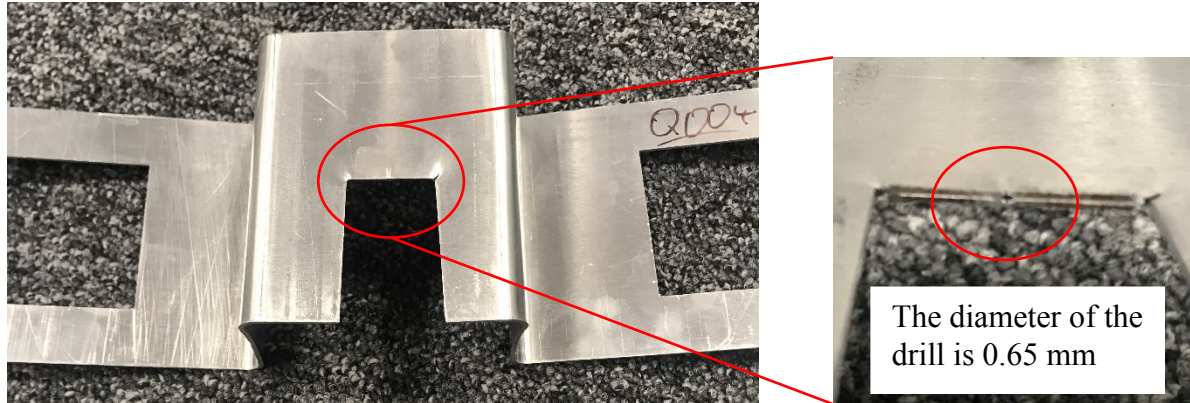


Figure A12 U-shape component for the temperature test during heating and forming process (The thermocouple was inserted into the middle hole of the blank as highlighted in the red circle)

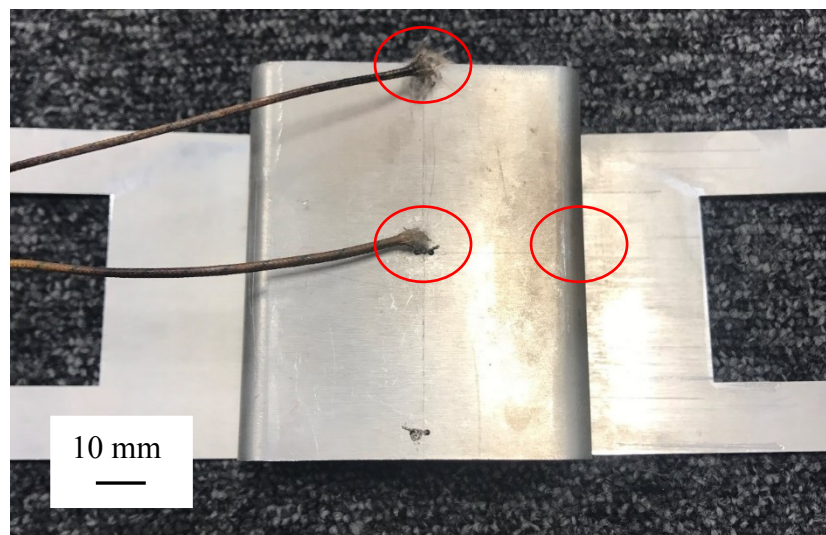


Figure A13 U-shape component for the temperature test of the incubation chamber (Three thermocouples were attached at three locations as highlighted in the red circle)

Appendix 3(b) Formed U-shape components using AA6082-T4 and -T6

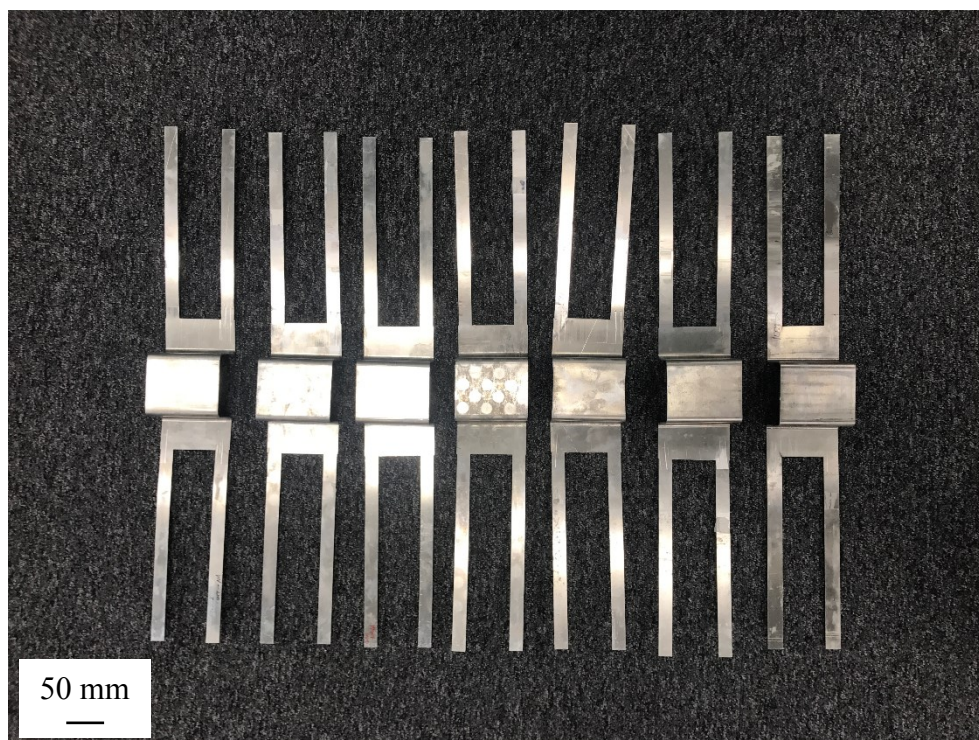


Figure A14 FAST formed AA6082-T4 U-shape components using Uni-Form

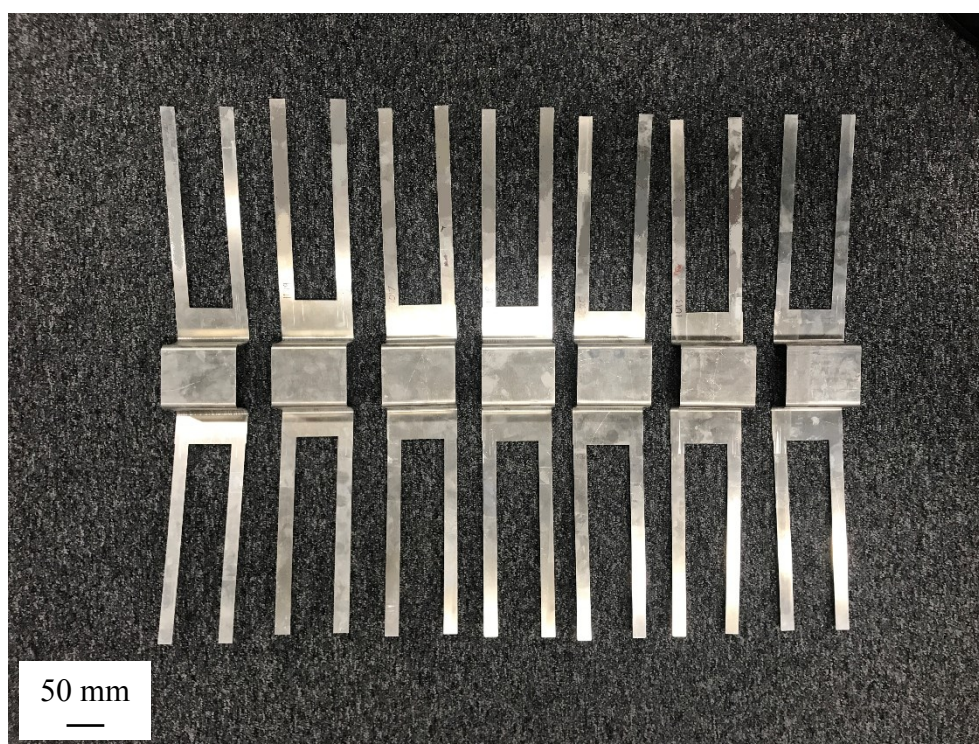


Figure A15 FAST formed AA6082-T6 U-shape components using Uni-Form

