Feasibility study on direct flame impingement heating applied for the solution heat treatment, forming and cold die quenching technique

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1. Introduction

High strength aluminium alloys, e.g. AA6082, AA6111 and AA7075, are suitable lightweight materials for manufacturing automobile body structures, which can provide a weight saving of up to 40% over steel in most applications without compromising safety [1]. These alloys have a moderately high stiffness to weight ratio, good weldability, recyclability, and a high level of corrosion resistance [2]. However, forming high strength aluminium sheets is challenging because of their relatively low formability and high springback at room temperature.

The solution heat treatment, forming and cold die quenching (HFQ) technique [3] was invented over 10 years ago and has been exclusively industrialised by Impression Technologies Ltd. as the world-first successful process for forming high strength complex shaped aluminium components. In a typical HFQ process, aluminium sheets are first heated to a target solution heat treatment temperature at which hardening phase particles, i.e. precipitates, are gradually resolved into aluminium matrix during soaking. The heat treated sheets are then transferred to a cold die press to be simultaneously formed and quenched [4,5]. A rapid heating method for solution heat treatment is required to increase productivity, and further reduce turnover cycle time, energy consumption and thus overall cost. This will significantly accelerate the adoption process of this highly enabling technique for the automotive industry.

Existing heating methods need to be optimised in order to considerably reduce the heat treatment time prior to forming, which is currently using a conventional electric or gas furnace. In addition, with the development of the HFQ process, predetermined temperature profiles in metallic blanks are required, which cannot be easily achieved using a conventional furnace. A comparison of existing heating methods for heat treatment of blanks for sheet metal forming applications has been carried out and presented in Section 2.

Unfortunately, none of these methods are suitable for high throughput heating of aluminium alloys in the HFQ process due to either low heating efficiency or low flexibility, which results in even higher system costs. Direct flame impingement (DFI) heating is an alternative method to realise rapid heating for aluminium sheets. It provides the advantages of a rapid heating rate, high heating efficiency, low energy consumption and high cost-effectiveness.

In this work, a feasibility study on the DFI heating applied, particularly, for the HFQ process is performed and presented in terms of achievable high heating rates, heating rate effect on surface quality for subsequent bonding, lap-shear strength and microstructure examination, and a comparison with the conventional furnace heating method is also shown in this paper.

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2. A review of current heating technologies for hot forming

Convection heating in a furnace using fuel or electricity has long heating time and low productivity. This heating method is currently widely adopted by the automotive industry for hot steel stamping due to its simplicity and availability. For example, 30–40 m long furnaces with an automatic conveying system are used to preheat steel blanks, for which at least 3-4 min heating time is required for a sheet thickness of 1.5–2.5 mm because of low heating efficiency [6]. The heating efficiency is even lower for heating aluminium sheet, since it can take over 5 min (roughly twice as long) for the same conventional furnace to heat an uncoated medium-size aluminium sheet with the thickness of 2 mm. These types of heating furnaces must be continuously operated to avoid long start-up delays in practical production, which would otherwise cause a drop in productivity.

A short heating time can be realised by resistance heating, which connects a sheet blank to electrodes alternatively to take current flow and to be heated by Joule’s effect, but it is feasible only for regular shape of blanks with favourable dimensions [7] and temperature uniformity is exceptionally challenging for hot stamping applications [8]. In the HFQ process, irregularly shaped aluminium sheets are usually fabricated and used for forming in order to enable a maximum draw in of sheet materials. Mori et al. [9] studied the application of rapid resistance heating for warm and hot stamping of sheet metals to reduce the oxidation and temperature drop during sheet transferring, but the non-uniform temperature field in the contact area between the electrode and the sheet was observed. It has been found that this method highly depends on the electric resistance and the shape of the metallic sheet [10] even if it tends to provide an efficient heating procedure for the small scale of the blank.

Although induction heating has been used extensively for tempering materials, it is not commonly used for heating metallic blanks because coil design is difficult for efficient heating, particularly for heating complex shaped blanks. Since induction heating [11] is a contactless heating method by using induction coils to induce eddy currents in an electrically conductive sheet within a specific distance, heating rate is determined by the frequency of the induced current and the material properties. The energy efficiency of induction heating is higher due to less heat loss compared to convection heating in a furnace, but it has low efficiency for heating non-ferrous metallic sheet with low magnetic permeability, such as aluminium alloy, and can suffer from temperature uniformity issues. Infrared heating [12] has similar issues and low efficiency, and it is inefficient for uncoated aluminium blanks and suffers similar temperature uniformity issues.

DFI heating offers an alternative method in metal forming processes for heating blanks by hot gas or flame generated via combustion of fuel, which increases significantly the heating efficiency and the heat transfer rate [13], because most of non-renewable electricity sources (coal, natural gas, nuclear, etc.) involve burning a fuel, which converts at best 45% of the heat produced into electricity. In a DFI furnace, a number of high speed burning jets are usually used to obtain high heat transfer efficiency from the combustion products to the load, and the arrangement of jets and operating parameters, such as nozzle dimensions, number of nozzles, distance between nozzles and the metal load, fuel supply and velocity of gas flow, need to be designed and optimised in order to realise uniform temperature distribution or predetermined temperature profiles in blanks. However, fundamental research on DFI [14] focuses on the investigation of combustion process, flame type and heat transfer processes, and it has not been studied for applications to sheet metal forming. A feasibility study is presented in the following sections to extend the applications of DFI to HFQ forming.

3. Methodology

3.1. Theoretical analysis of heating efficiency

According to the classic heat transfer theory, heat transfer formula can be expressed as Eq. (1), where Q is heat content in Joules, m is mass, c is specific heat and ΔT is a change in temperature. Heat transfer rate can be presented by Newton’s law of cooling in Eq. (2), where Φ is heat transfer, A is contact area, Δt is time difference and h is convective heat transfer coefficient which can be calculated by Eq. (3). Eq. (3) is an empirical equation proposed by Martin [15] in order to calculate the heat transfer coefficient NTU, where r is the distance from the centre of the workpiece, D is the diameter of the nozzle, H is the distance from the nozzle to the workpiece, λ and Pr are constants and Re is Reynolds number calculated by Eq. (4), where uc is the velocity of the air flow and ν is the kinematic viscosity of the air flow.

\[ Q = cmΔT \]  
(1)

\[ Φ = hAΔt \]  
(2)

\[ \frac{hr}{ΔT} = N_{TU} = 2 Re_0^{0.5}Pr^{0.42}(1 + 0.005 Re_0^{0.85}Pr^{0.3}) \frac{1 - 1.1D/r}{1 + 0.1(H/D - 6)D/r} \]  
(3)

\[ Re_0 = \frac{ucD}{ν} \]  
(4)

\[ N_{TU} = 0.54(GrPr)^{1/4} \]  
(5)

By the consideration of the radiation loss in Eq. (5), the relationship of heating time and temperature of the workpiece can be calculated. For a case study with parameters of the blank radius r of 40 mm, distance from nozzle to the workpiece H of 30–55 mm and a nozzle diameter of 30 mm, the effects of distance H and air flow velocity uc (in a range of 2–8 m/s) on the heating rate are shown in Fig. 1. The flame temperature can be estimated by using Adiabatic flame temperature calculator and fuel is methane (CH₄) with an equivalence ratio of 1.0.

Based on the theoretical model introduced previously, it can be seen that the heating rate of an aluminium blank with a diameter of 40 mm and a thickness of 1.5 mm can be almost doubled if the velocity of air flow is raised from 2 m/s to 4 m/s, but less improvement can be observed if velocity of air flow is raised further from 4 m/s to 8 m/s. Only around 10% temperature difference can be obtained at a different velocity of air flow when the distance from nozzle to workpiece is changed from 30 mm to 55 mm.

3.2. Experimental programme of DFI heating

3.2.1. Material and specimen

Aluminium alloy 6082 sheets of T6 temper with the thickness of 1.5 mm and the diameter of 180 mm (as seen in the Fig. 2), which is one
of the most promising high strength aluminium alloys for automotive parts production, were chosen as an exemplar and used for the comparison of DFI heating and furnace heating under the HFQ conditions. The chemical composition of AA6082 is shown in Table 1, for which different compositions of the sheets will affect the formation of chemical components on the surface layer of samples during the heat treatment. K-type thermocouples were welded on the mid-width line of the specimen along the diameter at the centre (T1) and the distance of 40 mm (T2) in order to monitor the temperature history and temperature gradient during the heating.

3.2.2. Experimental set-up

Fig. 3 shows the experimental set-up in a combustion unit. The unit is made of air rotameters, fuel, swirl mixing chamber and combustion. The flow was controlled by a software system in order to determine the velocity of gas flow and fuel equivalence ratio accurately. The lower combustion unit with the diameter of 30 mm was used first, which was considered to be sufficient since the thickness of the sample was only 1.5 mm. The distance between the sample and lower nozzle was initially set to 55 mm. Thermocouples attached to the sample sheet on the top surface were connected to a data logger to record the temperature history. The entire combustion unit was operated in an open environment for this study.

4. Results and discussion

4.1. DFI heating for aluminium alloys sheets

4.1.1. Effect of fuel equivalence ratio

Fig. 4 shows the comparison of temperature history by using pure methane (CH4) (equivalence ratio = 1.0) and 80% methane (CH4) (equivalence ratio = 0.8). The velocity of gas flow was 2 m/s. Temperature was measured at the central point, T1 (solid lines in Fig. 3) and the location of 40 mm, T2 (dash lines in Fig. 3). It was found that heating rate of central point was 13.3 °C/s by using pure methane in an open environment and it was 10.6 °C/s by using 80% methane instead. Compared to the average heating rate of 2–3 °C/s measured in a thermal furnace for the same size of blank, it was about 4–5 times improvement in terms of heating rate. The maximum temperature difference of 60 °C within a diameter of 40 mm was observed during the heating process. The uniformity of temperature distribution can be affected by many factors, such as the distance between blank and nozzle, velocity of gas, flame temperature, heat loss during heating and open or closed environment, etc. These parameters can be optimised easily in order to further increase the heating efficiency.

4.1.2. Effect of gas flow rate

The effect of gas flow rate on the heating rate of samples is shown in Fig. 5. In an open environment, heating rate of central point T1 in the circular sample was 13.3 °C/s when gas flow rate was 2 m/s and heating rate of central point T1 increased to 25.1 °C/s when gas flow rate increased to 4 m/s. This means that the heating rate can be doubled if gas flow rate is doubled. Rapid heating rate can be achieved efficiently by DFI heating. DFI heating would be also more flexible for the heating process than heating metal sheets in a furnace for the aim of predetermined temperature profile in a metal sheet since the parameters for DFI can be controlled independently. The maximum temperature difference of 85 °C within a diameter of 40 mm was observed in an open environment, but this can be decreased by optimising heating parameters in future. It is also observed that dual nozzles heating from the top and bottom side of the metal sheet can double the heating rate, and heating efficiency can be improved in a closed environment since the heat loss from fuel burning would be reduced significantly.
4.1.3. Discussion

An array of such high-velocity flame jets impinging on a workpiece can be designed and optimised to provide a uniform or predetermined heating and temperature profile in a metal sheet, once the DFI heating method is integrated to HFQ. A schematic of DFI module arrangement is shown in Fig. 6, which can be used for heating up metallic blanks by connecting DFI modules to a controllable software system. The obtained heating rate and temperature profile using DFI demonstrated that, compared to heating in a furnace, significantly higher heat transfer rate at the surface of the metal sheet and considerably lower heat loss can be achieved using a DFI furnace. But further optimisation of operating parameters and heating environment is required to perform in future in order to achieve a higher heating rate and more uniform temperature distribution in the workpiece.

4.2. Characterisation analysis of surface layer and cross section

4.2.1. Heat treatment of samples

Various HFQ testing temperature profiles of heating and cooling processes for AA6082 are shown in Fig. 7. The aluminum sheet was heated to the solution heat treatment temperature in a range of 525–545 °C [16] at a heating rate of 1.8, 3, 30 °C/s to allow the hardening precipitates to dissolve into solid solution matrix. Once the temperature of the specimen reached the programmed one, various soaking time was selected for solution heat treatment in a range of 1 s to 1 min, and then water quenched to room temperature, which maintained a supersaturated solid solution in the material. A standard ageing process of 9 h at 190 °C was applied after to enable fine and well-distributed hardening precipitates to appear in order to regain alloy’s strength. A test matrix of conditions by DFI and thermal furnace is presented in Table 2. Surface layer analysis was performed under each testing condition.

100 mm × 25 mm × 1.5 mm samples of AA6082 were DFI heated using the same heating facility, as shown in Fig. 3, to study the changes of surface layer after DFI heating. One pair of K-type thermocouples was attached on the side of the sample along the width direction, and connected to a data logger in order to record temperature history. In contrast, for furnace heating, to make a better comparison of surface layers with a similar heating rate, a target temperature of 525–545 °C was reached on two steel blocks. These two blocks then directly clamped an aluminium sample to achieve a high heating rate from 20 to 36 °C/s. It is noticed that, in this case, heating rate can only be achieved at 1.8 to 3 °C/s in the absence of two hot blocks in the furnace.

4.2.2. Results of wettability tests

The presence of oxide layers or contaminants on the surface of an AA6082 sample can significantly reduce the subsequent bonding property for assembly. In order to quantify this effect, contact angle is used to measure the wettability, an important bonding or adherence parameter, of the solid surface by a liquid [17]. In general, less than 90° of contact angle is considered to be hydrophilic and larger than 90° of

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**Table 2**

<table>
<thead>
<tr>
<th>Heating rate (°C/s) by DFI</th>
<th>Heating rate (°C/s) in Furnace</th>
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</thead>
<tbody>
<tr>
<td>Heating rate (°C/s)</td>
<td></td>
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<tr>
<td>Soaking time (s)</td>
<td>1 s</td>
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<tr>
<td>30 s</td>
<td>√</td>
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<td>60 s</td>
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<tr>
<td>20 °C/s</td>
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<td>30 °C/s</td>
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<td>60 °C/s</td>
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**Fig. 5.** The effect of gas flow rate on heating rate (solid lines show temperature measured at the central point of the blank (T1) and dash lines show temperature measured at the distance to mid-length of 40 mm (T2)).

**Fig. 6.** Flexible array of DFI modules.

**Fig. 7.** Temperature profile of heating, quenching and ageing processes of AA6082.
contact angle is considered to be hydrophobic. The smaller the contact angle, potentially the better for subsequent bonding properties.

Fig. 8 shows the results of contact angle measurement after different heat treatment processes by DFI and furnace. The values of contact angle for samples after heat treated by DFI are in a range of 61.7°–74.0°, which are higher than those of as-received samples and samples heat treated in a furnace (38°–53.3°). This suggests that the surface condition was changed to some extent even if only CO₂ and H₂O were generated from fuel burning. After subsequent 9 h ageing process in the furnace, contact angles reduced slightly by 5%–15% at most of the conditions. Although furnace heated samples showed more hydrophilic characteristics than DFI treated samples, all samples had contact angles less than 86°, which are the cases of being hydrophilic.

4.2.3. Results of surface layer examination

Surface chemistries of samples were examined by FTIR (Fourier-transform infrared spectroscopy) which is one of the most versatile and powerful techniques for the characterisation of materials’ surface and element analysis. The analysed results are shown in Fig. 9. A range of various surface chemistries is observed for all samples with quite thin oxide layers. Both heating rate and soaking time can affect the levels of chemistries in oxide layers of samples. The hydrocarbon (C–H) and magnesium in the oxide films are high for relatively long DFI treated time compared to those for furnace treated samples, which potentially caused low wetting characteristics. Nevertheless, the levels of hydrocarbon, hydration (OH), absorbed water and magnesium oxide (MgO) decreased significantly after ageing process conducted in a furnace, especially for DFI heated samples with long soaking time, which would improve the surface quality for subsequent bonding. With a short soaking time of DFI heating, there was a little difference in surface layer analysis between samples with ageing and samples without ageing.

In a typical HFQ process for aluminium alloys, only a short soaking time is required while a high heating rate is applied during the heating process in order to reduce grain growth which would potentially deteriorate strength, ductility and toughness. Therefore, according to the results of wettability (Fig. 8) and surface layer quality analysis (Fig. 9), DFI heated samples are comparable to those of conventional furnace heated ones under high heating rates and short soaking time.

4.2.4. Microstructure of sample cross section

The microstructure (grain structure) at the cross sections of heat-treated samples were revealed, as seen in Fig.10, by an optical microscope under polarised light. The samples were mechanically ground and polished with OPS to a mirror finish and then anodised the polished cross-sections using Barker’s reagent at 20–30 V for 1–2 min at ambient temperature.

Similar grain structure, compared to as-received materials, was revealed for the furnace heated samples, except the sample treated in a relatively high heating rate (20 °C/s) and long soaking time (30 s) which has largely coarser grains close to sample surface along the cross section. This means that, for the material of AA6082, long soaking time at a high heating rate in a furnace could cause grain growth in the material and low heating rate is beneficial for avoiding rapid grain growth. Similarly, no obvious inhomogeneous grain structure distribution was found in the DFI heat treated samples under various heat treatment conditions, as shown in Fig. 10(b); therefore, grain growth along sample cross section is not notable, which potentially improve material strength and ductility. However, according to Fig. 10(c), grain growth can be generally observed after the ageing process in a furnace, especially for sample pre-DFI treated at a heating rate of 20 °C/s and
soaking time of 30 s. In summary, DFI heating will not affect the uniformity of grain distribution but heating in a furnace with a high heating rate and long soaking time can result in rapid grain growth in the material, which could affect mechanical properties of AA6082, such as low ductility and low material strength.

4.3. Measurement of lap-shear strength

4.3.1. Adhesive bonding procedure
Lap-shear strength test was used to investigate the bonding strength of DFI and furnace heated samples after the analysis of the wettability and surface layer (Section 4.2.2 and 4.2.3). In this work, single lap-shear strength test was conducted by stretching a single-overlap joint between a rigid assembly. It is the most widely used method to obtain shear strength of bonded products due to its simplicity [18]. According to the standard BS ISO 4587:2003, the shape and dimensions of the assembled specimen are defined in Fig. 11. The bonded region is 12.5 mm × 25 mm and clamping region for tensile tests is 37.5 mm × 25 mm. The same conditions were applied, as shown in Table 2, to all heat treated samples. The samples were assembled by using the automotive adhesive of Dow Betamate 2098, which is a two component 200 μm glass beads containing epoxy-based adhesive, especially developed and commonly used for the body shop and the repair of vehicles [19]. Bonding area was cleaned with heptane, clamped and cured at 60 °C for 2 h. The thickness of the adhesive is 0.2 mm. Spacers were used between the grip and the assembly during shear strength testing by a universal tensile test machine so that the applied force can be applied to the adhesive bond and no extra bending was generated to the assemblies. The test procedure was referred to the standard of ASTM D 1002.

4.3.2. Comparison of the lap-shear strength of AA6082 heated by DFI and furnace
Fig. 12 shows results of the lap-shear strength of AA6082 assemblies treated by DFI and furnace at a range of heating rates and soaking time. As-received materials presented 40% cohesion failure mode and the majority of other bonds after heat treatment presented adhesive failure mode. It was found that all samples after heat treatment had lower shear strength than as-received samples. Long soaking time after a rapid heating process decreased the shear strength of the corresponding assembly. The DFI treated samples have slightly better average shear strength compared to the furnace treated ones. It is noted that the adhesive or surface cleaning process used in this paper may not be the most promising one. Further improvement in the shear strength of bonded samples can certainly be achieved as demonstrated by successful adhesive bonding of furnace heat treated car parts.
5. Conclusions

Feasibility study of DFI has been carried out to develop a more efficient and effective heating method in order to further improve the productivity of the HFQ process. The rapid heating rate of over 10 °C/s has been obtained by DFI on AA6082 sheets of 1.5 mm. Various heating profiles applied to HFQ technique were designed and achieved by using the proposed DFI heating and conventional furnace heating methods, respectively. By conducting a vigorous study of effects on material properties, including surface layer chemistry, wettability, bonding strength and microstructure variation, the DFI method is demonstrated as a promising feasible, energy-efficient and cost-effective method to perform heat treatment for aluminium alloys by integrating in the HFQ process, and thus potentially improve the productivity. The evidenced conclusions can be drawn: 1) hydrophilic surface of AA6082 samples treated by DFI and furnace is beneficial for adhesive bonding; 2) surface layer of DFI heated samples are comparable to those of conventional furnace heated under high heating rates and short soaking time; 3) DFI heating can reduce grain growth in AA6082 which usually occurred when heating in a furnace with a long soaking time; 4) bonding shear strength of assemblies heat treated by DFI and furnace is similar, but optimal surface cleaning and bonding processes need to be further investigated.

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