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Development of an interfacial heat transfer coefficient model for the hot and warm aluminium stamping processes under different initial blank temperature conditions

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Abstract

Different initial blank temperatures, or forming temperatures, are applied in hot and warm aluminium stamping processes depending on the component being formed and the desired post-form properties. An initial blank temperature dependent interfacial heat transfer coefficient is therefore an essential boundary condition in such non-isothermal forming processes for obtaining precise temperature fields from the formed components in finite element simulations. This precision is crucial for the optimisation of the processing window and tool design, to subsequently achieve the desired cooling rates and post-form strength of the aluminium components being formed. The IHTC between a 7075 aluminium alloy and tungsten carbide cobalt coated cast-iron was found to approximately increase linearly with increasing initial blank temperature in the present research. The effect of the initial blank temperature was identified as a combination of two mechanisms; the effects of material strength and thermal conductivity. The IHTC was found to decrease with increasing strength of the blank when the contact pressure was lower than a threshold value, while a larger thermal conductivity of the aluminium blank increased the IHTC values. Furthermore, an initial blank temperature-dependent model was developed to predict the IHTC at different initial blank temperatures, which was subsequently verified by the results of non-isothermal forming tests.

Keywords: Interfacial heat transfer coefficient; Initial blank temperature; Hot and warm stamping; 7075 aluminium alloys

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1. Introduction

The application of aluminium alloys in light-weight vehicles has been widely studied to reduce carbon emissions and improve fuel economy, as stated by Toros et al., (2008). Recently, elevated temperature stamping technologies were developed to form sheet aluminium alloys to increase their formability, which was shown in the study of Gao et al., (2017). Additionally, these technologies could also decrease springback, as described by Wang et al., (2017). Solution heat treatment, forming and in-die quenching (HFQ) is one such technology, in which an aluminium alloy blank is first heated up to its solution heat treatment (SHT) temperature, e.g. 535°C for 6082 aluminium alloys in the study of J. Liu et al., (2018) and 480°C for 5754 aluminium alloys in the study of El Fakir et al., (2014), and then deformed and simultaneously quenched by cold tools at a rapid cooling rate. Consequently, a supersaturated solid solution is obtained to ensure that a high post-form mechanical strength in the aluminium alloy is fully obtained after a suitable ageing process. In the hot stamping process developed by Maeno et al. (2017), an aluminium alloy blank in the T4 state is quickly heated by electrical resistance heating to a target temperature lower than the SHT temperature, dissolving the solute atoms in the aluminium matrix. Subsequently, the hot blank is deformed by cold tools into the desired shape. Warm stamping technologies have also been developed to form sheet aluminium alloys at elevated temperatures below their recrystallisation temperatures, moderately improving their formability while maintaining the high strength of the blank material. In the study of Palumbo and Tricarico, (2007), an aluminium alloy blank, die and blankholder are first heated to 100-300°C and then deformed by a cold punch under non-isothermal conditions. Additionally, initial blank temperatures, i.e. forming temperatures, in between the SHT and recrystallisation temperatures, e.g. 200-500°C, have been applied in some established warm and hot aluminium alloy stamping technologies, that are dependent only on the formability required to form a component with the desired geometry successfully, as stated by Cai et al., (2018).

In such non-isothermal warm and hot stamping processes, a hot blank is deformed by cold forming tools, and thus heat transfer occurs. The interfacial heat transfer coefficient (IHTC) is therefore an essential boundary condition in such forming technologies for obtaining precise temperature fields from the formed components in finite element (FE) simulations, as described by Karbasian and Tekkaya (2010). By using a precise definition of the IHTC by J. Liu et al., (2017), the processing window and tool design were subsequently optimised to attain the critical cooling rate. Hence, the IHTC has been characterised in previous research to study its influential factors. Different trends of the IHTC were found as the contact pressure was

increased, e.g. an exponential trend shown by X. Liu et al., (2018), a power trend shown by Chang et al., (2016) and a linear trend shown by Caron et al., (2014), due to a larger real contact area and thus heat transfer occurring at higher contact pressures. Additionally, the IHTC decreased with the application of low thermal-conductive tool coatings, e.g. glass-based coatings in the study of Bai et al., (2012). However, it increased by the application of high thermal-conductive tool coatings, e.g. silver-based coatings in the study of Li et al., (2000). In order to predict the IHTC evolutions as a function of contact pressure and tool coating, Liu et al., (2019) developed a mechanism-based model, which was then implemented via a Cloud Based Finite Element simulation platform developed by Wang et al., (2018), to enable the multi-objective FE simulation of a hot stamping process.

In these previous studies, the IHTC values were determined at specific initial blank temperatures. However different stamping processes utilise different initial blank temperatures, or forming temperatures, that depend on the component being formed and the desired post-form properties. In the present research, the IHTC was therefore determined at different initial blank temperatures between a 7075 aluminium alloy and uncoated/tungsten carbide-cobalt (WC-Co) coated cast-iron. The effects of the contact pressure, tool coatings and initial blank temperature on the IHTC were characterised and then predicted by a developed initial blank temperature-dependent IHTC model. The determined results and developed model were subsequently validated by using the results of hot and warm stamping tests under different initial blank temperature conditions.

2. Method to determine the IHTC

2.1 Experimental setup

The inverse FE simulation method was used to identify the IHTC for 7075 aluminium alloys, in which the experimental temperature evolutions of an aluminium alloy (Al) specimen were first measured and then compared with those obtained from FE simulations to determine the corresponding IHTC value under the selected test conditions. A test facility developed by (X. Liu et al., 2017) was integrated into a Gleeble 3800 machine to conduct the IHTC tests and measure the experimental temperature histories. The uncoated/coated punches and dies (No. 2 in Fig. 1) supplied by Association Industry Navarra (AIN) were bolted onto pedestals (No. 1 in Fig. 1), as shown in Fig. 1 (a). The substrate material of the punch and die was a cast-iron, and their contact surface areas were $50 \times 25 \text{ mm}^2$, onto which a WC-Co coating with a thickness

of 2 μm was deposited for one set of tools. The average surface roughness (R_a) of the contact surfaces was approximately 180 nm for both the uncoated and coated tools.

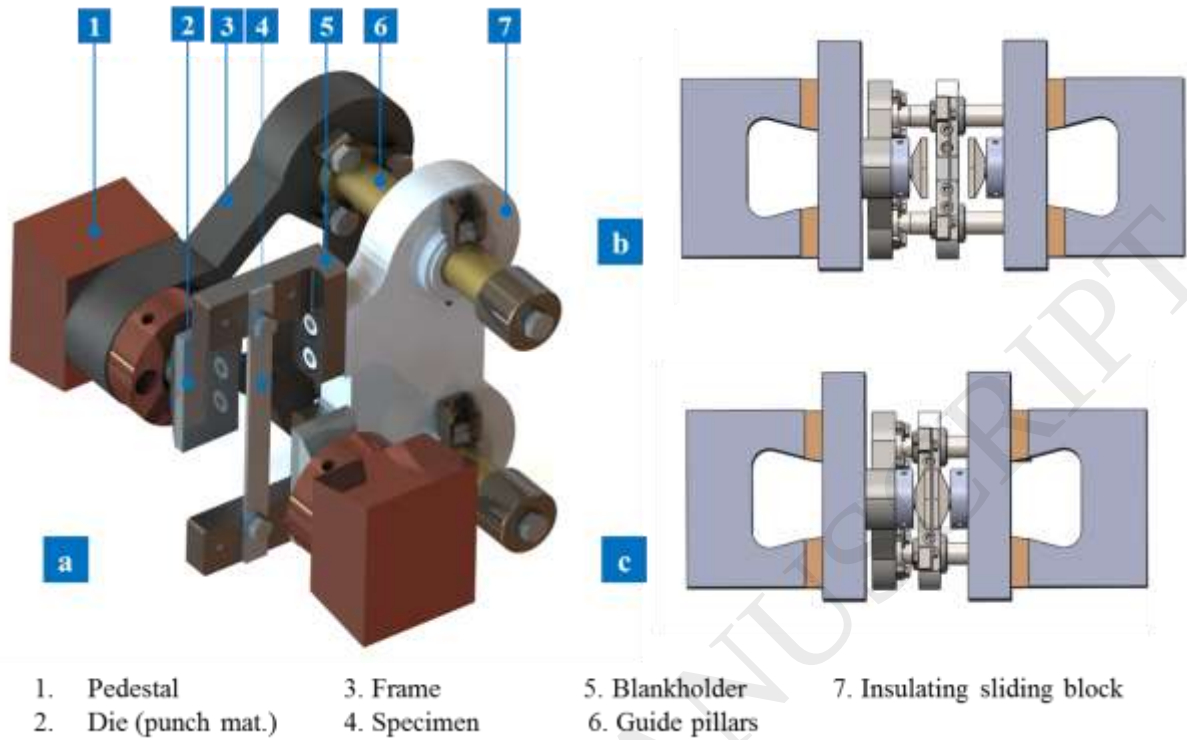


Fig. 1. (a) The applied IHTC test rig; (b) The IHTC experiment under unloading conditions; (c) The IHTC test under loading conditions.

A 2 mm thick AA7075-T6 specimen with a size of 120 x 10 mm² (No. 4 in Fig. 1) was fixed onto two cast iron blankholders (No. 5 in Fig. 1), which were then bolted onto an insulating sliding block (No. 7 in Fig. 1). Thermocouples (k-type) were located at the centre of the Al specimen to measure its experimental temperature history. In each test, the Al specimen was first heated by the Gleeble to the target temperature, while the tools were kept at room temperature. After heating the blank, the cold punch was immediately moved along the guide pillars (No. 6 in Fig. 1) horizontally to contact the Al specimen with the static die, followed by compression at a defined contact pressure for 20 seconds. Table 1 shows the applied test matrix, while Fig. 1 (b) and (c) show schematics of the IHTC test under unloading and loading conditions respectively.

Table 1. The IHTC test matrix.

	Temperature					
Contact pressure	Coated	Uncoated	Coated	Uncoated	Coated	Uncoated
	350°C		420°C		470°C	
0.5 MPa	√	√	√	×	√	√
5 MPa	√	√	√	×	√	√
20 MPa	√	√	√	×	√	√
30 MPa	√	√	√	×	√	√
40 MPa	√	√	√	×	√	×
50 MPa	√	√	×	×	√	×

2.2 Finite element simulation setup

A FE model shown in Fig. 2 was developed in the stamping simulation software PamStamp, in which the geometries of the components were identical to those used in the IHTC tests. Explicit quadrangle (4-nodes) thermal-mechanical shell elements of $2 \times 2 \text{ mm}^2$ were applied for the aluminium specimen. In order to reduce the computational time, mass scaling was activated for the simulations, and as confirmed by Fig. 3, this did not affect the quality of the simulation result. Fig. 3 also shows the temperature at the centre of the specimen at 4 seconds as a function of mesh size from 1 to 5 mm. It was found that the temperature was converged at approximately 149.7°C when the mesh size was smaller than 2 mm. Above 2 mm, the temperature increased with increasing mesh size. This study proved that a mesh size of 2 mm would ensure accurate simulations while providing reasonable computational times.

The material properties of AA7075 determined by Johnson, (2004) and cast-iron shown in Table 2 were assigned as material cards in the simulations. The temperature of the cast-iron tools increases during compression, and at the contact surfaces reached a high value of 80°C when the IHTC was $1 \text{ kW/m}^2\text{K}$ and the initial blank temperature was 470°C , as shown in Fig.

4. It has been proven by Holmgren (2005) that the thermal conductivity of cast-iron only increases slightly when its temperature is lower than 100°C, and the temperature of the forming tools does not affect the IHTC within that range as stated by Mendiguren et al., (2016). Therefore, the thermal and mechanical properties of the cast iron tools supplied by AIN were considered constant, with negligible influence on the simulated results.

Table 2. Thermal and mechanical properties of AA7075 and cast-iron.

Property	Units	AA7075 (T in Kelvin)	Cast iron
Young's modulus	GPa	$-39.08e-3 \cdot T + 82.53$	169
Density	kg/m ³	$-6.75e-5 \cdot T^2 - 0.15 \cdot T + 2860.8$	7100
Thermal conductivity	kW/mK	$-5.145e-8 \cdot T^2 + 1.37e-4 \cdot T + 8.5e-2$	0.0352
Specific heat capacity	J/kgK	$8.72e-7 \cdot T^3 - 1.46e-3 \cdot T^2 + 1.2 \cdot T + 608.3$	490
Poisson ratio	---	$3.89e-8 \cdot T^2 + 1.35e-4 \cdot T + 0.325$	0.26

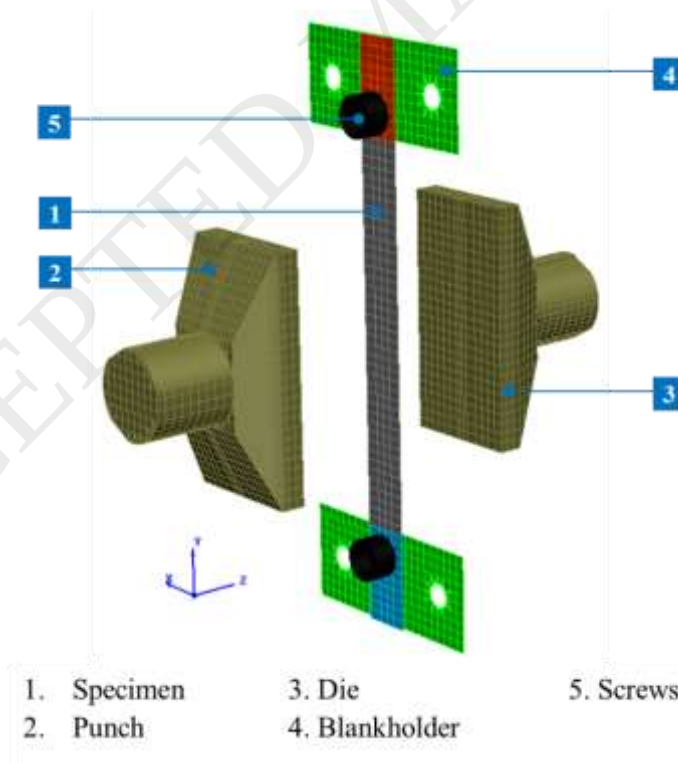


Fig. 2. The finite element model setup.

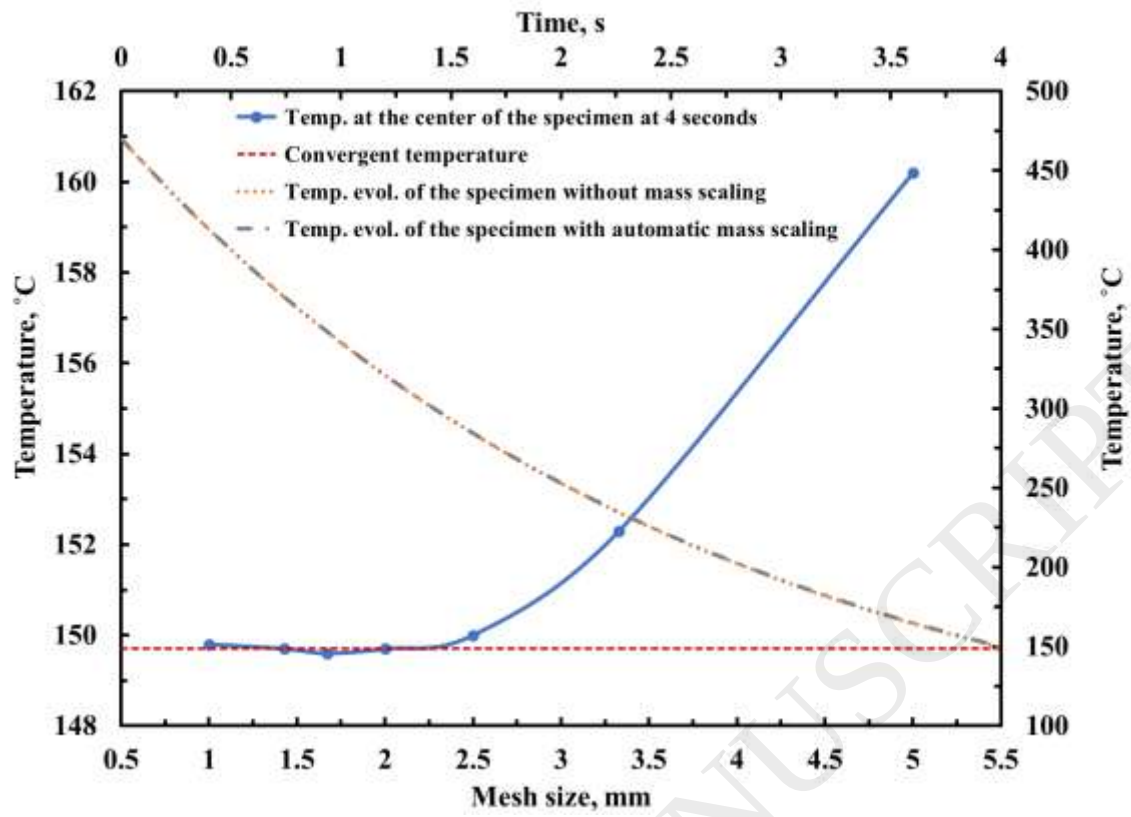


Fig. 3. The mass scaling and mesh convergence studies.

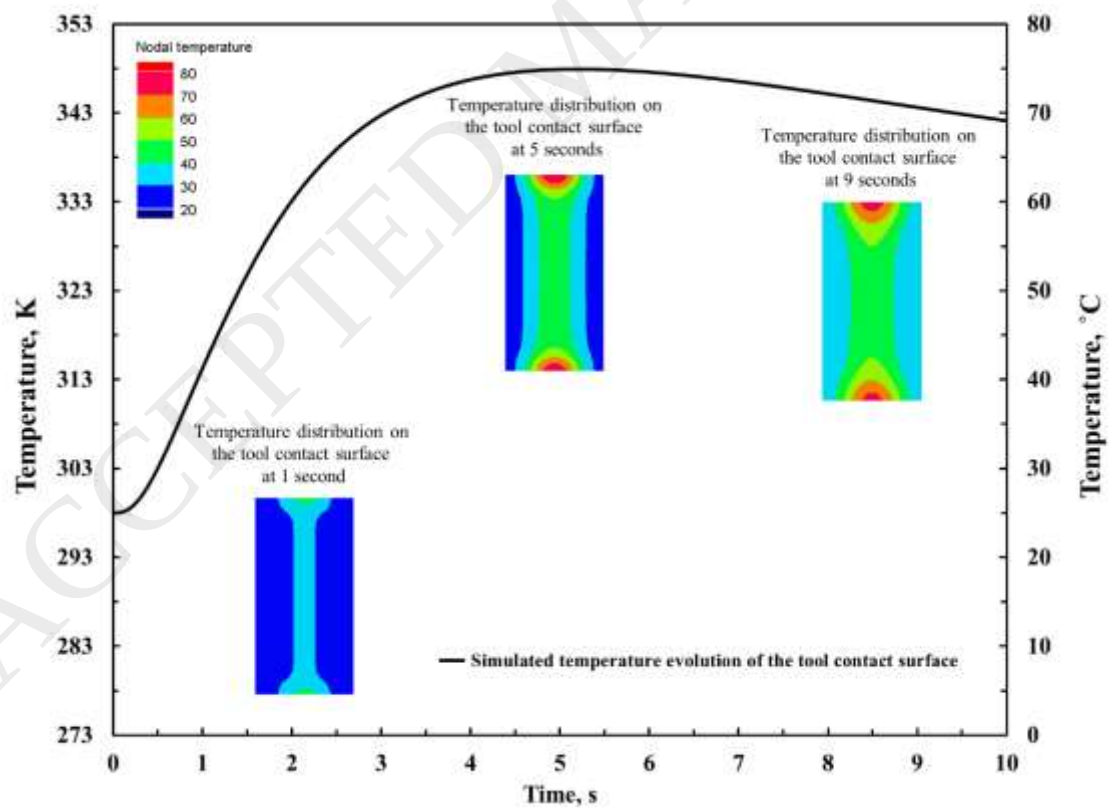


Fig. 4. The temperature evolution and distribution at the tool contact surface for an IHTC value of 1 $\text{kW/m}^2\text{K}$ and an initial blank temperature of 470°C .

The simulation process was composed of four steps, i.e. gravity, holding, stamping and quenching. Firstly, the Al specimen was freely placed onto the blankholders along the z-direction and then fixed into position by the screws. Subsequently, the punch was rapidly moved along the z-direction and compressed the Al specimen against the die. The processing parameters, e.g. initial temperature and speed, were the same as those applied in the IHTC test, while a constant IHTC was applied in the FE simulation as a decisive boundary condition to constrain the heat transfer between the hot specimen and cold tools, by removing the potential influences of the contact pressure, coating and surface roughness. The temperature histories of the Al specimen during compression were then simulated at a series of constant IHTC values from 0.5 to 10 kW/m²K and compared with experimental results under a specific test condition. When the error between a simulated and experimental curve was minimized (generally below 5%), the agreement between them was considered best, indicating that the IHTC value assigned to generate that simulated curve represented the value under that specific test condition.

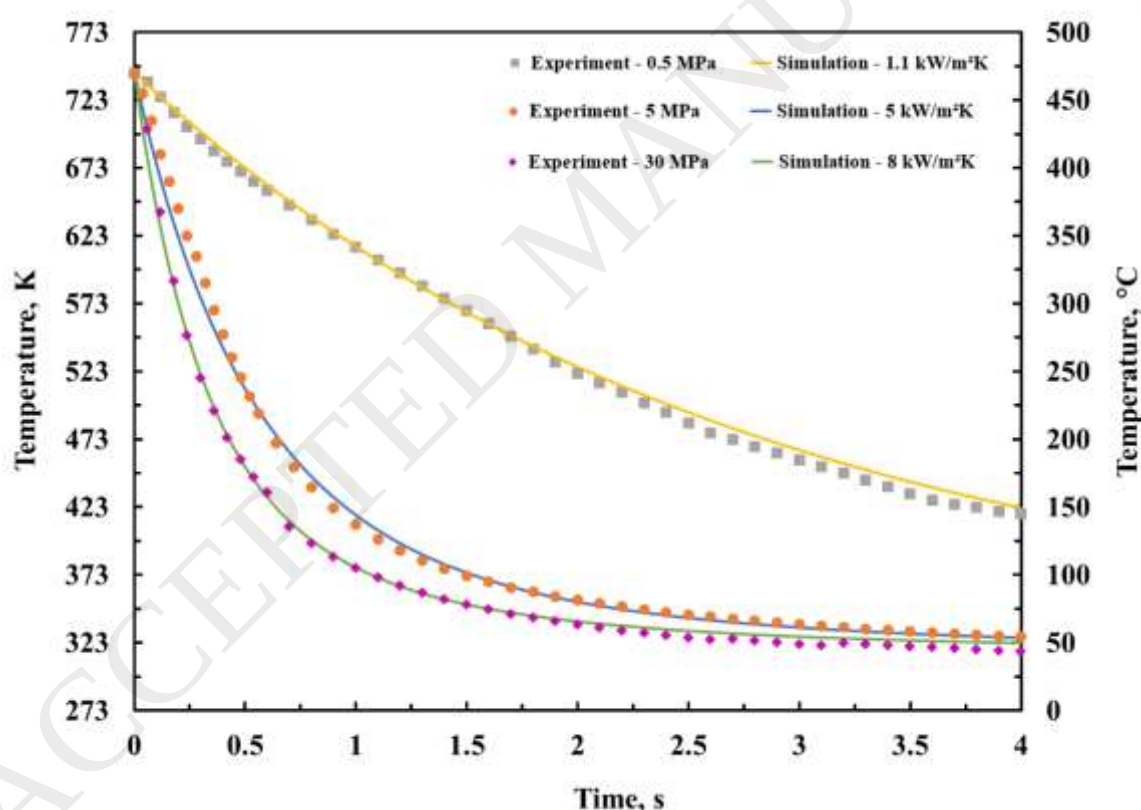


Fig. 5. The experimental and temperature histories of the AA7075 specimen and cast iron die at different contact pressures of 0.5, 5 and 30 MPa.

As shown in Fig. 5, the simulated curves that best compared with the experimental results with minimum errors of 2.1%, 3.4% and 4.3% indicated that the IHTC between AA7075 and the

WC-Co-coated tool was 1.1, 5 and 8 kW/m²K at the contact pressures of 0.5, 5 and 30 MPa respectively, when the initial blank temperature was 470°C. Meanwhile, the good agreement between the experimental and simulated results with average errors below 5% proved that the heat transfer between the hot Al specimen and cold tools could be characterised by a stable IHTC value under a certain test condition. Therefore, it was reasonable to assume the IHTC as a constant value in the FE simulations to predict the temperature evolutions of the Al specimen.

3. Results and discussions

The IHTC for the 7075 aluminium alloy under different experimental conditions was identified. As shown in Fig. 6, the increasing trends of the IHTC evolutions with pressure were similar when using different initial blank temperatures. However, the IHTC was observed to rise with increasing initial blank temperature. The effects of the contact pressure, tool coating and initial blank temperature on the IHTC are analysed in the following sections.

3.1 Contact pressure effect on the IHTC

As shown in Fig. 6, when using WC-Co-coated cast iron tools, the IHTC for 7075 aluminium alloy was found to increase significantly from 1.1 to 8 kW/m²K with increasing pressure from 0.5 to 20 MPa at an initial blank temperature of 470°C and stabilised at a value of approximately 8 kW/m²K after 20 MPa. The characterised IHTC evolutions with contact pressure followed a similar logarithmically increasing trend when applying different initial blank temperatures, although their convergent contact pressure values were different.

Asperities existed on the contact surfaces of both the aluminium specimen and steel tools. As a result, the real contact area was considerably smaller than the apparent value between the Al specimen and tools prior to each compression, as stated by Buchner et al., (2009). Meanwhile, the hot aluminium alloy was significantly softer than the cold cast-iron. Therefore, the aluminium asperities were deformed and then meshed to those on the tool surfaces during compression. Consequently, the real area enhanced with larger pressures, thus leading to larger IHTC. However, once the real contact area reached the apparent value, the peak IHTC was achieved and would no longer be affected by the increasing contact pressure.

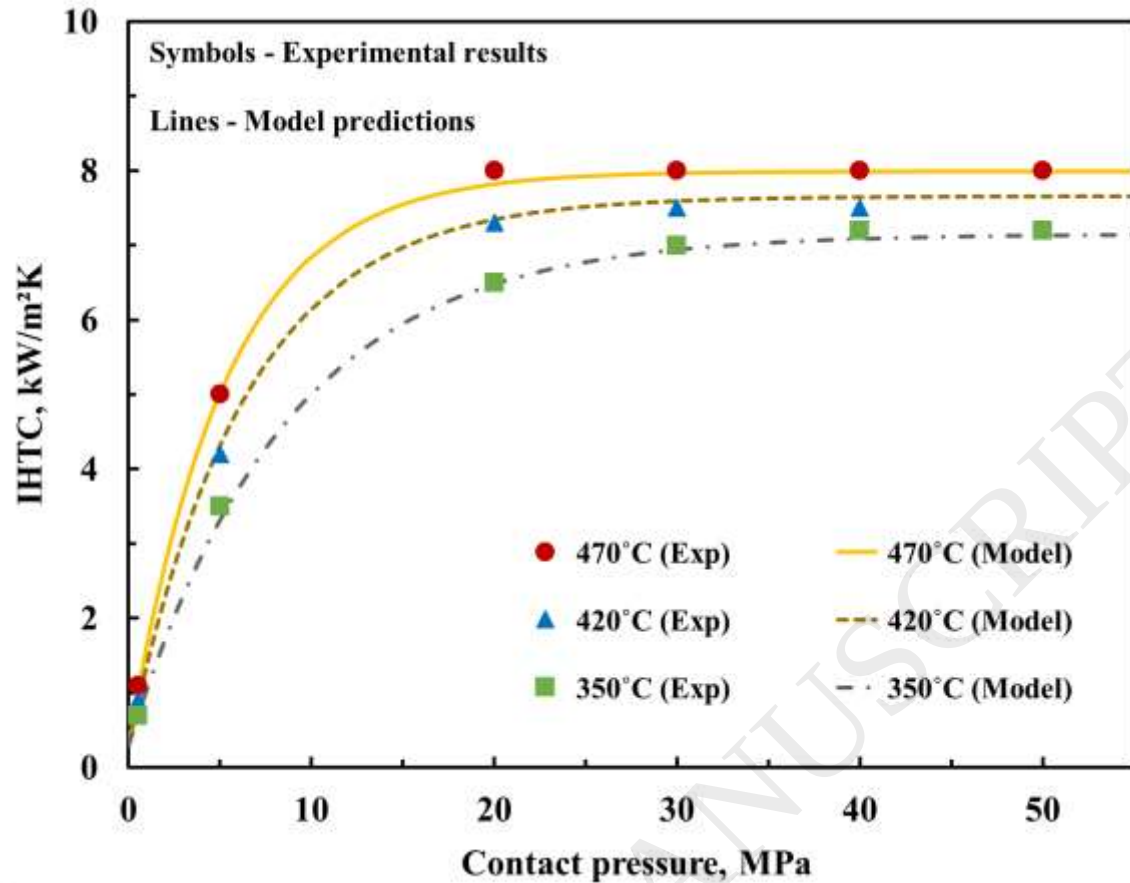


Fig. 6. The IHTC evolutions for the 7075 aluminium alloys determined by the experiments and predicted by the model at different contact pressures and initial blank temperatures, when WC-Co-coated cast-iron tools were used.

3.2 Coating effect on the IHTC

When using the uncoated cast-iron tools, the IHTC for the 7075 aluminium alloy increased rapidly from 1.5 kW/m²K at 0.5 MPa to 10.5 kW/m²K at 20 MPa. A plateau of the IHTC at higher contact pressures at an initial blank temperature of 470°C was then observed, as shown in Fig. 7. The IHTC values were found to decrease by the application of the WC-Co coating at the same initial blank temperature. At an initial blank temperature of 350°C, the IHTC for AA7075 increased significantly from 0.9 to 9.5 kW/m²K as a result of the increasing pressure from 0.5 to 30 MPa, when the uncoated tools were used. A similar decrease in the IHTC was also found when WC-Co-coated tools were used at the same initial blank temperature. As the thermal conductivity of the WC-Co coating (292 W/mK) was lower than that of the cast iron (353 W/mK), thus heat conduction across the coating layer was consequently reduced, resulting in lower IHTC values. Therefore, the application of tool coatings with thermal conductivities

lower than those of the substrates could reduce the IHTC, which has also been deduced in the study of Liu et al., (2019).

Table 3. Decreases in the IHTC due to the application of the WC-Co coating.

623K (350°C)			
Pressure (MPa)	IHTC (Uncoated) (kW/m²K)	IHTC (Coated) (kW/m²K)	Decrease in the IHTC %
5	4.5 (±0.8)	3.5 (±0.8)	22.2%
20	8.5 (±0.5)	6.5 (±0.8)	23.5%
30	9.5 (±0.4)	7 (±0.4)	26.3%
743K (470°C)			
Pressure (MPa)	IHTC (Uncoated) (kW/m²K)	IHTC (Coated) (kW/m²K)	Decrease in the IHTC (%)
5	6.5 (±0.5)	5 (±0.5)	23.1%
20	10.5 (±0.5)	8 (±0.6)	23.8%
30	10.5 (±0.6)	8 (±0.5)	23.8%

At 5 MPa, the IHTC values were decreased by approximately 22.2% and 23.1% due to the application of the WC-Co coating at initial blank temperatures of 350°C and 470°C respectively, as shown in Table 3. Furthermore, it was found that the amount of decrease in the IHTC caused by the WC-Co coating was always between 22% and 27%, with an average value of 24%, at different initial blank temperatures and contact pressures. It could therefore be deduced that the thermal properties of the WC-Co coating, particularly its thermal conductivity, were negligibly changed when the initial blank temperature increased from 350°C to 470°C. Therefore, the effect of the tool coating on the IHTC was consistent for different initial blank temperatures and did not cause the variation in the IHTC at different initial blank temperatures.

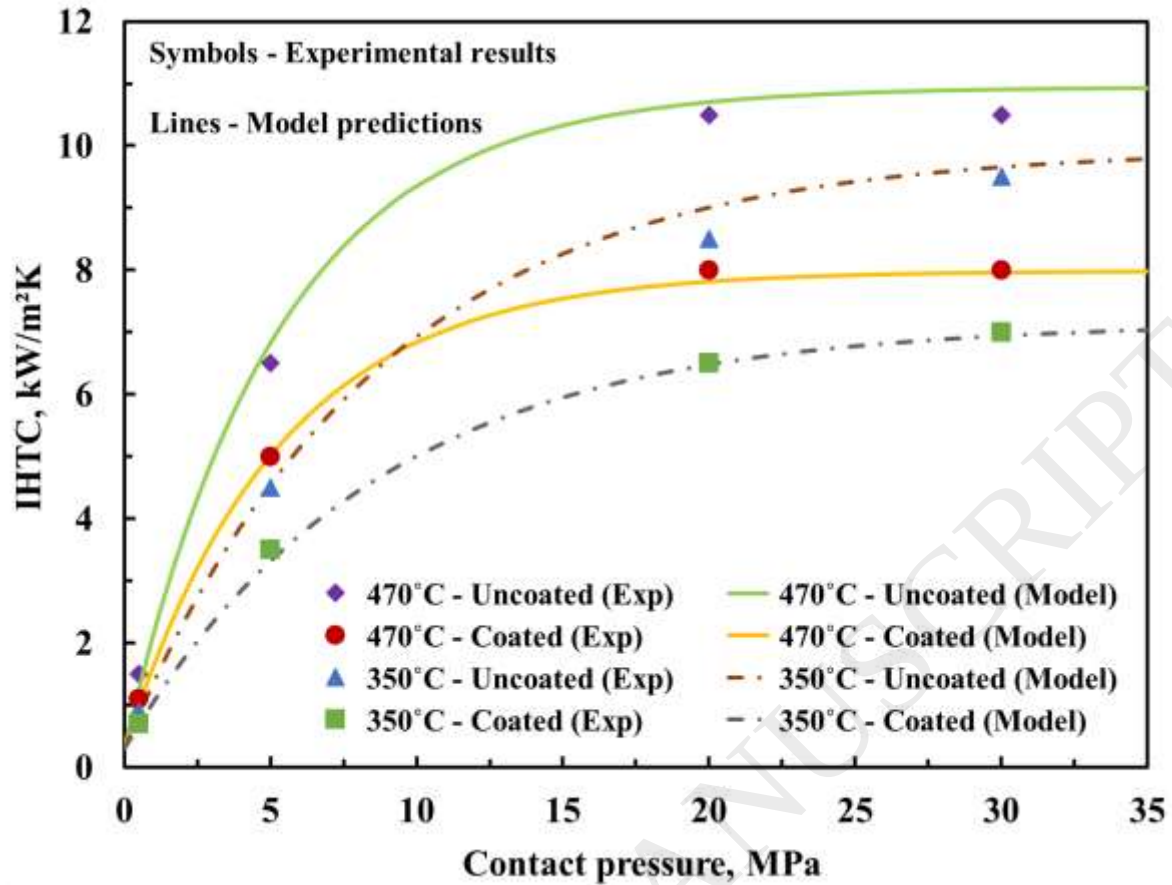


Fig. 7. The IHTC evolutions for the 7075 aluminium alloys determined by the experiments and predicted by the model at different contact pressures and initial blank temperatures, when uncoated and coated cast-iron tools were used.

3.3 Initial blank temperature effect on the IHTC

The IHTC was decreased by 16% at a contact pressure of 5 MPa when the initial blank temperature was reduced from 470°C to 420°C, as shown in Table 4. However, the amount of decrease in the IHTC decreased with increasing pressure and reached a constant value of 6.3% once the convergent contact pressure of 30 MPa was achieved. Similarly, when the initial blank temperature decreased from 470°C to 350°C, the amount of decrease in the IHTC decreased from 30% at 5 MPa to 12.5% at 30 MPa and reached a constant value of 10% after the convergent contact pressure of 40 MPa. It was found that the effect of the initial blank temperature decreased with increasing contact pressure and became constant when the convergent contact pressure was reached. The effect of the initial blank temperature on the IHTC could therefore be categorised into two stages dominated by two mechanisms respectively.

The material strength of aluminium alloys decreases with increasing initial blank temperature. Therefore, the deformation of the AA7075 specimen surface increased with increasing initial blank temperature at the same contact pressure, resulting in a larger real contact area and IHTC value. However, the convergent contact pressure decreased with increasing initial blank temperature due to the achievement of the peak contact area at a lower contact pressure.

Table 4. Decreases in the IHTC as a result of the decreasing initial blank temperature from 470°C to 350°C.

Pressure (MPa)	IHTC (470°C) (kW/m ² K)	IHTC (420°C) (kW/m ² K)	IHTC decrease (470 to 420°C)	IHTC (350°C) (kW/m ² K)	IHTC decrease (470 to 350°C)
5	5 (±0.5)	4.2 (±0.6)	16%	3.5 (±0.8)	30%
20	8 (±0.6)	7.3 (±0.7)	8.8%	6.5 (±0.8)	18.8%
30	8 (±0.5)	7.5 (±0.3)	6.3%	7 (±0.4)	12.5%
40	8 (±0.5)	7.5 (±0.5)	6.3%	7.2 (±0.3)	10%

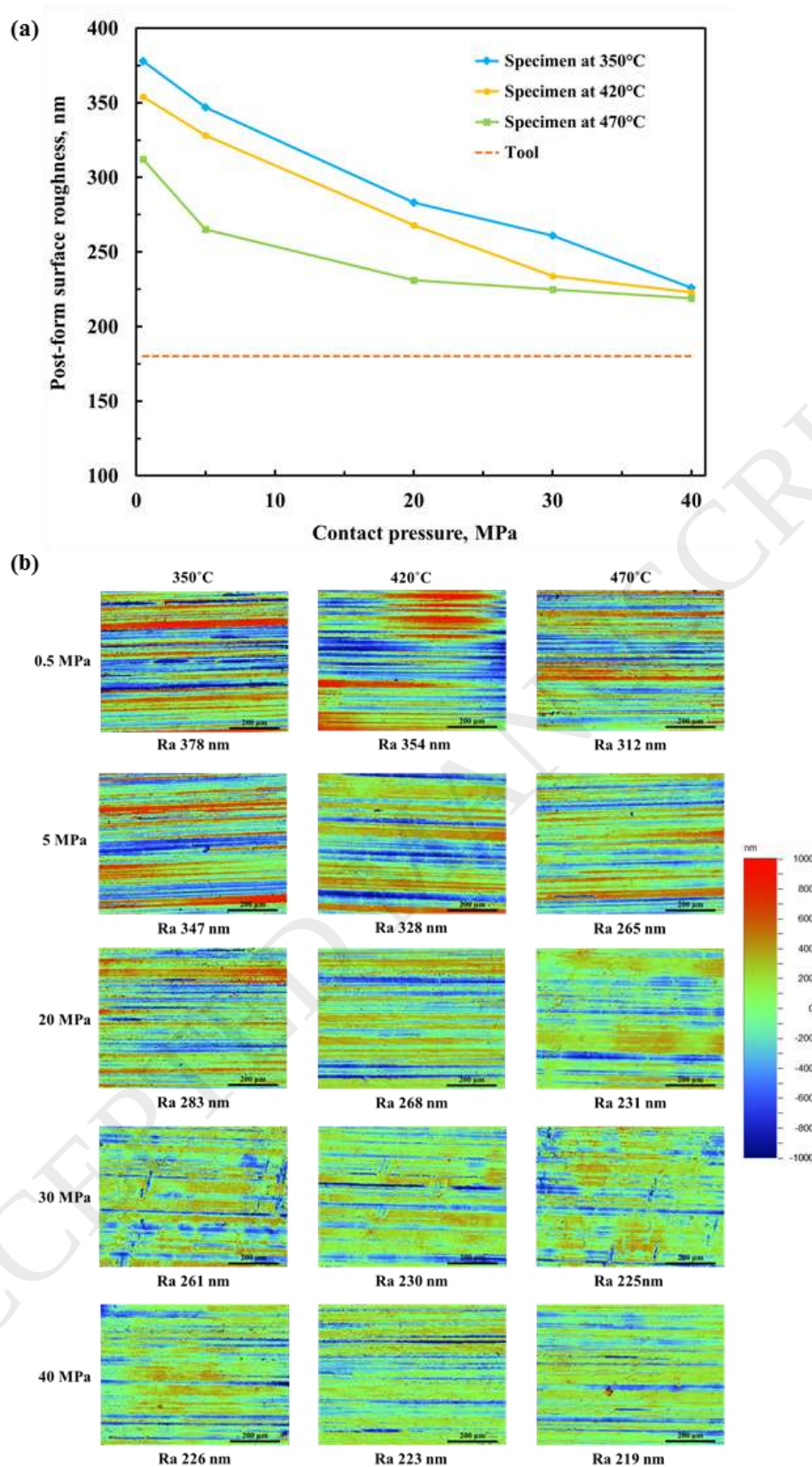


Fig. 8. (a) Post-form Ra of the AA7075 specimen with pressure at different initial blank temperatures; (b) White light interferometry scanned post-form surface roughness results of the Al specimen under different experimental conditions.

The average post-form surface roughness (Ra) of the aluminium contact surface under different experimental conditions was measured to describe its deformation. The initial Ra of the Al specimen and tool were 390 and 180 nm respectively. As shown in Fig. 8, when the initial blank temperature was 350°C, the post-form surface roughness of the specimen decreased from 378 nm at 0.5 MPa to 226 nm at its convergent contact pressure of 40 MPa, approaching that of the tool. When the initial blank temperature was 420°C, the post-form Ra of the Al specimen was 354 nm at a contact pressure of 0.5 MPa and decreased to 230 nm after 30 MPa, while it decreased from 312 to 231 nm as a result of the increasing pressure from 0.5 MPa to its convergent value of 20 MPa when the initial blank temperature was 470°C.

From these results, it could be deduced that the post-form Ra of the Al specimen was lower at a higher initial blank temperature, representing a better mesh and thus a larger real contact area at the interface. When the convergent contact pressure was reached, the Ra of the Al specimen after compression was close to that of the tools at different initial blank temperatures. Therefore, the material strength of the aluminium specimen at different initial blank temperatures affected the IHTC before the convergent contact pressure was reached. However, this effect reduced with increasing contact pressure and became negligible at the convergent contact pressure.

The differences in the IHTC at different initial blank temperatures after the convergent contact pressure was reached were caused by the variations in the thermal properties of the aluminium alloy specimen. The thermal conductivity and specific heat capacity of the Al specimen decreased with decreasing initial blank temperature, thus reducing the heat transfer at the interface. Chang et al., (2016) has shown that the specific heat capacity of the specimen has a negligible influence on the IHTC. Therefore, the variation in the thermal conductivity of the aluminium alloy specimen resulted in different IHTC values. When the initial blank temperature decreased from 470°C to 420°C, the thermal conductivity of the specimen was decreased by 2% from 158 to 155 W/mK. The IHTC was consequently decreased by approximately 6.3%, as shown in Table 4. Additionally, a decrease from 470°C to 350°C in the initial blank temperature caused a decrease of 5% from 158 to 150 W/mK in the thermal conductivity of the specimen, leading to a decrease of 10% in the IHTC.

Hence, the effect of the initial blank temperature on the IHTC was composed of two mechanisms; the influences of the material strength and thermal conductivity. When the contact pressure was lower than its convergent value, the material strength of the aluminium alloy specimen was the leading mechanism, but once the convergent contact pressure was reached,

the variation in the thermal conductivity of the Al specimen became the dominant mechanism affecting the IHTC.

4. Initial blank temperature-dependent IHTC model

During compression, heat is transferred from the hot specimen, first to the vacancies at the contact interface, then to the coating layer if applicable, and finally to the forming tools. These three mediums and their unique mechanisms affect the heat transfer and thus determine the IHTC. Although a coating is deposited onto the tools as a whole solid contact surface, its contribution to the IHTC is independent of the contribution from the solid contact between the Al specimen and cast-iron tools. Therefore, the effect of the coating on the IHTC should be studied as an independent part to sufficiently describe the particular functions of the material properties of the coating. As a result, the overall IHTC was considered as a sum of three variables, modelled by Eq. (1). Meanwhile, this linear superposition based on the independent heat transfer mediums is beneficial to individually investigate the influential factors, e.g. initial blank temperature, on the IHTC.

$$h = h_a + h_s + h_c \quad (1)$$

where h_a is the null-pressure IHTC, describing the minor heat flow across the vacancies between the aluminium alloy blank and forming tools as a constant value, h_s is the solid-contact IHTC, describing the considerable heat transfer across the interface, and h_c is the coating-contact IHTC, representing the influence of the coating on the IHTC.

The solid-contact IHTC h_s was represented by Eq. (2), where α is a model constant, and K_{st} R_{st} are the harmonic mean thermal conductivity and the r.m.s. surface roughness of the interface respectively, which allows the prediction of the IHTC when using different tool materials.

$$h_s = \alpha \frac{K_{st}}{R_{st}} N_p \quad (2)$$

The pressure-dependent parameter N_p describes the deformation process of the Al specimen and thus represents the relationship between the IHTC and contact pressure, as shown in the study of Cooper et al., (1969). It was represented by Eq. (3), where γ , P and σ_U are the model constant, contact pressure and ultimate mechanical strength of the Al specimen respectively.

$$N_p = 1 - \exp\left(-\gamma \frac{P}{\sigma_U}\right) \quad (3)$$

The coating-contact IHTC h_c accounts for the amount of heat transferred across the applied coating layer and was represented by Eq. (4), where β , A , δ_c and k are the model constant, apparent contact area, applied coating thickness and thermal conductivity respectively, of which subscripts s , c and t indicate the Al specimen, coating and tool respectively. The term $\ln(k_c/k_t) \cdot \delta_c$ is a function of the thermal conductivity ratio of the coating to the substrate (tool) and the coating layer thickness and represents the coating effect.

$$h_c = \beta \frac{k_s \ln(k_c/k_t)}{A} \delta_c N_p \quad (4)$$

In order to predict the IHTC evolutions with initial blank temperature, the identification and development of temperature-dependent parameters in the model were necessary. According to the results of the IHTC tests, the tool coating was independent of the initial blank temperature in its effect on the IHTC. Therefore, the model parameter β was maintained as a constant value. In contrast, the material strength and thermal conductivity of the Al specimen contributed to the initial blank temperature-dependent IHTC. Hence, the ultimate strength of the Al specimen σ_U and the model parameter α could be identified as temperature-dependent parameters. Arrhenius equations have been widely applied to describe the thermodynamic behaviour of metallic materials at elevated temperatures, e.g. aluminium alloys from 200°C to 550°C as stated by El Fakir et al., (2014), titanium alloys from 600°C to 950°C as stated by Kopeck et al., (2018) and boron steels from 600°C to 900°C as stated by Li et al., (2013). Therefore, Arrhenius equations were applied in the present research to model the temperature-dependent parameters for aluminium alloys within the temperature range of 200°C to 500°C, as shown by Eqs. (5 and 6). In addition, the thermal conductivity of the Al specimen $k_t(T)$ was set as a temperature-dependent material property, as characterised in Table 2.

$$\sigma_U(T) = \sigma_0 \exp\left(\frac{Q_\sigma}{RT}\right) \quad (5)$$

$$\alpha(T) = \alpha_0 \exp\left(\frac{Q_\alpha}{RT}\right) \quad (6)$$

where σ_0 and Q_σ are model constants, determined through tensile tests at elevated temperatures at a strain rate of 1 s^{-1} , while α_0 and Q_α are model constants, determined using different values of α at elevated temperatures, as shown in Table 5. R is the universal gas constant, and T is the temperature in Kelvin.

Table 5. σ_U and α at elevated temperatures.

Parameter	Temperature		
	623K (350°)	693K (420°C)	743K (470°C)
σ_U (MPa)	120.7	88.6	73.7
α (-)	7.27e-5	7.68e-5	7.94e-5

Table 6. Parameters of the IHTC model.

Parameter	h_a (kW/m ² K)	γ (-)	β (-)	R_s (m)	R_t (m)
Value	0.2	14	2.5e4	1.8e-7	3.9e-7
Parameter	k_t (kW/mK)	k_c (kW/mK)	A (m ²)	δ_c (m)	α_0 (-)
Value	0.0352	0.0292	5e-4	2e-6	1.26e-4
Parameter	σ_0 (MPa)	Q_σ (J/mol)	Q_α (J/mol)	R (J/molK)	
Value	5.69	15810.61	-2845.93	8.31	

All 17 model parameters are shown in Table 6, from 6 parameters, γ , β , α_0 , σ_0 , Q_σ and Q_α , were calibrated using experimental data. The developed initial blank temperature-dependent model was therefore able to predict the IHTC evolutions with initial blank temperature as well as contact pressure, tool and coating materials.

To highlight the initial blank temperature effect, the IHTC evolutions with initial blank temperature at three contact pressures of 8, 15 and 60 MPa were predicted by the model and shown in Fig. 9. This indicated that the IHTC approximately increased linearly with increasing initial blank temperature, with the rate of increase decreased with contact pressure, which agreed with the experimental results. Although a linear relationship between the initial blank temperature and the overall IHTC was observed, a simple empirical model was not able to accurately describe the mechanism of the initial blank temperature on the IHTC. Therefore, the

development of the initial blank temperature-dependent IHTC model is of great importance to transfer the present findings to other materials.

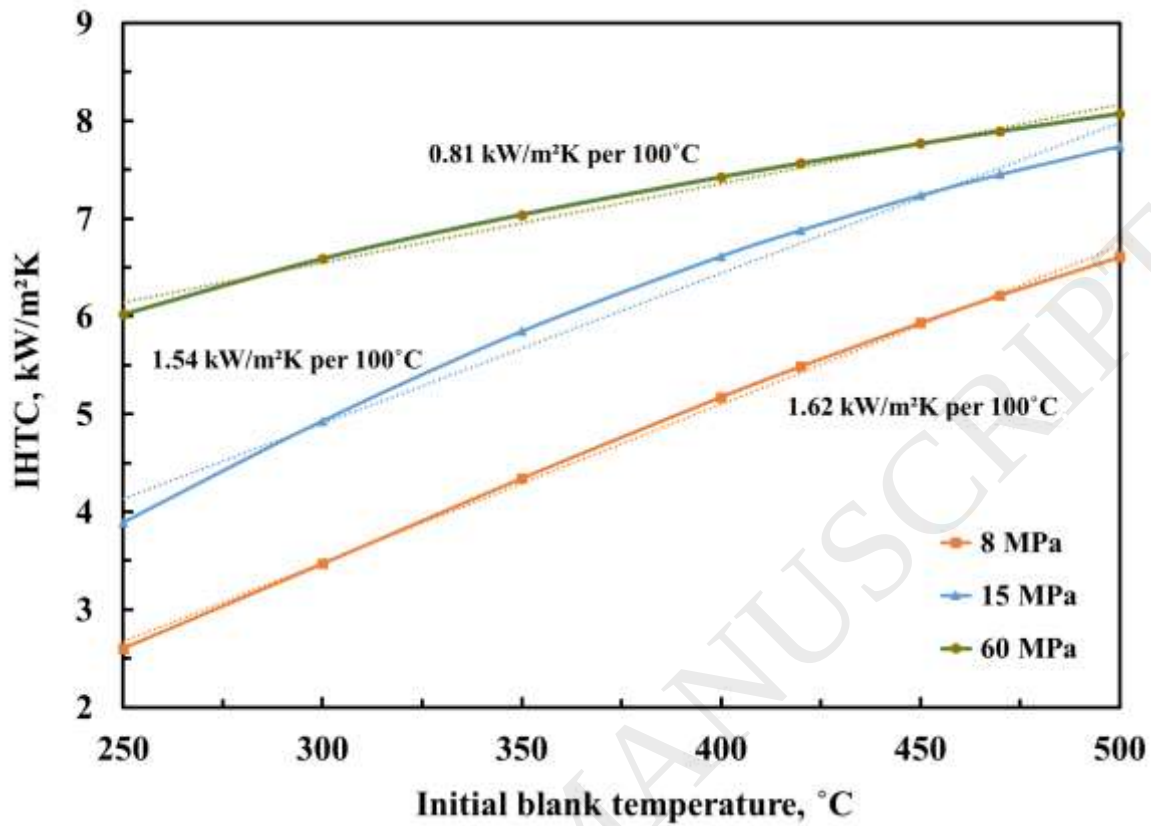


Fig. 9. The IHTC curves for AA7075 as a linear function of initial blank temperature at different contact pressures.

5. Hot and warm stamping validation tests

U-shaped components were deformed at different initial blank temperatures to validate the experimental results and developed initial blank temperature-dependent IHTC model. As identified by Harrison and Luckey, (2014), an initial blank temperature of 470°C was utilised to represent the typical hot stamping 7075 aluminium alloys, while 200°C was used as the initial blank temperature to represent typical warm stamping processes, which was identified by Huo et al., (2016). U-shape forming tools were manufactured and assembled onto a 100-tonne ESH press, as shown in Fig. 10 (a). A 240 x 84 x 2 mm³ AA7075 blank (No. 2 in Fig. 10 (a)) was first heated to the target temperature and then rapidly transferred onto blankholders (No. 3 in Fig. 10 (a)), which were screwed onto a support plate (No. 4 in Fig. 10 (a)). After that, a punch (No. 1 in Fig. 10 (a)) was immediately moved towards the blank to compress it against the blankholders. Four gas springs (No. 6 in Fig. 10 (a)) connected to the support plate, provided a blankholding force up to 80 kN. As the punch motion progressed, the blank was

deformed by a fixed die (No. 5 in Fig. 10 (a)) into a U-shaped component, as shown in Fig. 10 (b). A thermocouple was welded onto the side wall of the blank at its mid-point and connected to a thermometer to record the temperature history.

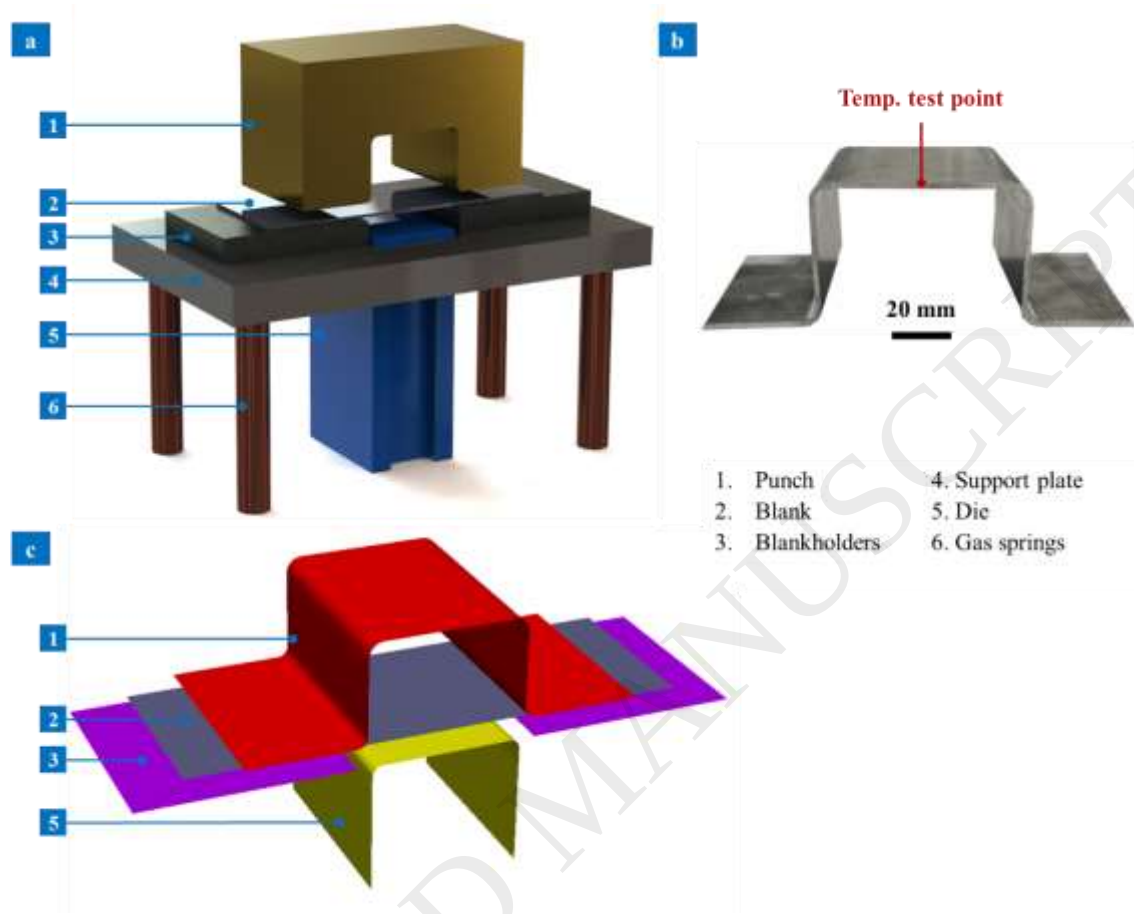


Fig. 10. (a) Structure of the U-shape forming tools; (b) The formed U-shaped component; (c) FE model of the U-shape forming process.

Meanwhile, a FE model was also developed to simulate the hot and warm stamping processes of the U-shaped component, as shown in Fig. 10 (c). Variations in the IHTC due to the tool surface roughness changes, caused by *e.g.* wear and (or) galling *etc.*, was not studied in the present research. However, in the FE simulation of a stamping process under multi-cycle loading conditions, an interactive IHTC model, *e.g.* X. Liu et al., (2018), may be developed and implemented to predict the evolutions of the IHTC values as a function of surface roughness changes.

The geometries and materials of each component were the same as those used in the experiments. Processing parameters identical to the experiments, *e.g.* initial temperature, moving speed and die-closing force, were used in the simulation, while the IHTC evolutions for AA7075 at initial blank temperatures of 470°C and 200°C with contact pressure were

predicted by the developed model and then used in the simulation to acquire the temperature history of the aluminium blank, as shown in Fig. 11. In order to simulate the heat transfer between the blank and air, a heat transfer coefficient of $20 \text{ W/m}^2\text{K}$ defined by Bai et al., (2012) was applied in the FE simulation.

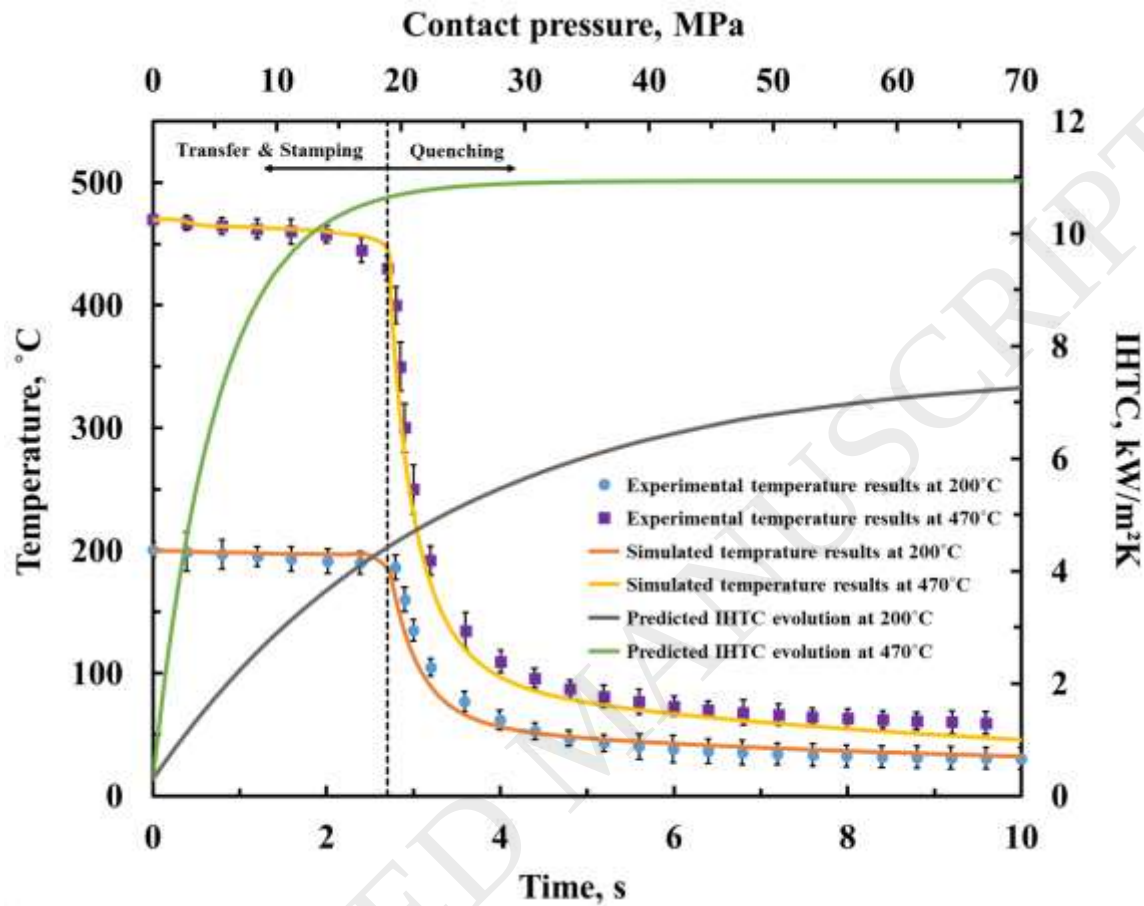


Fig. 11. Temperature histories of the U-shaped components measured by the experiments and predicted by the FE simulations; and the implemented IHTC evolutions for AA7075 with contact pressure at two initial blank temperatures of 470°C and 200°C .

In the FE simulation of the U-shape forming process, the blank (No. 1 in Fig. 10 (c)) was first freely positioned on the blankholders (No. 2 in Fig. 10 (c)) and then compressed by the punch (No. 1 in Fig. 10 (c)). Subsequently, the compressed blank was deformed by the die (No. 5 in Fig. 10 (c)) into the U-shape. After quenching for 20 seconds, the punch and blankholder were returned to their initial positions, and the temperature history was recorded. As shown in Fig. 11, the temperature decreased slowly up to 2.3 seconds, representing the transfer and stamping stages, and dropped dramatically afterwards, representing the quenching stage. The temperature evolutions from these processing stages were thus successfully captured in the experiments and accurately predicted by the FE simulation, and provided successful validation

of the IHTC results and model. The developed model was therefore able to accurately predict the IHTC evolutions with contact pressure, initial blank temperature, forming tools and tool coatings.

6. Conclusions

To characterise the interfacial heat transfer coefficient for the non-isothermal hot and warm aluminium stamping processes, the IHTC between 7075 aluminium alloy and tungsten carbide cobalt coated cast-iron was determined under different initial blank temperature conditions. The research findings are summarised as follows:

- The IHTC approximately increased linearly with increasing initial blank temperature at the same contact pressure, independent of the tool coating effect. The effect of the initial blank temperature was identified as a combination of two mechanisms; the effects of the material strength and thermal conductivity.
- The IHTC was affected by the strength of the aluminium alloy specimen when the contact pressure was lower than its convergent value, i.e. the IHTC increased with decreasing material strength due to a larger deformation occurring at a higher initial blank temperature.
- The effect of material strength became negligible after the convergent contact pressure, while the growing thermal conductivity of the Al specimen became the dominant mechanism, further increasing the IHTC values.
- An initial blank temperature dependent IHTC model was developed to predict the IHTC evolutions with contact pressure, initial blank temperature, forming tools and tool coatings. The results of the non-isothermal forming of U-shaped components at different initial blank temperatures validated the developed model.
- The IHTC and temperature evolutions of the components formed in the non-isothermal hot and warm aluminium stamping tests under different initial blank temperature conditions could be simulated accurately, and could therefore be used to optimise processing windows to achieve the desired cooling rates and thus retain the post-form mechanical strength of aluminium components being formed.

The present research studied and modelled the effects of the initial blank temperature, contact pressure and tool coating on the IHTC for a specific combination of tool and specimen material. However, the applied IHTC test facility enables the flexible interchange of the specimen and tools made from different materials and the precise control of initial blank temperature and

contact pressure. Therefore, the applied methodology and test facility are also applicable to the determination of the IHTC for other target material combinations and processing parameters. Subsequently, the developed IHTC model would provide a prediction to guide the tests and thus reduce the experimental efforts. Hence, the present findings show a good transferability to the identification of the IHTCs for other material combinations.

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