

Characterization of the interfacial heat transfer coefficient for hot stamping processes

Xi Luan, Xiaochuan Liu, Haomiao Fang, Kang Ji, Omer El Fakir and LiLiang Wang *

Department of Mechanical Engineering, Imperial College London, SW7 2AZ, UK

E-mail: liliang.wang@imperial.ac.uk

Abstract. In hot stamping processes, the interfacial heat transfer coefficient (IHTC) between the forming tools and hot blank is an essential parameter which determines the quenching rate of the process and hence the resulting material microstructure. The present work focuses on the characterization of the IHTC between an aluminium alloy 7075-T6 blank and two different die materials, cast iron (G3500) and H13 die steel, at various contact pressures. It was found that the IHTC between AA7075 and cast iron had values 78.6% higher than that obtained between AA7075 and H13 die steel. Die materials and contact pressures had pronounced effects on the IHTC, suggesting that the IHTC can be used to guide the selection of stamping tool materials and the precise control of processing parameters.

1. Introduction

Due to growing concerns about fuel economy improvement and exhaust emissions reduction, there has been a remarkable growth in the development of new forming technologies applied in the automobile and aviation industries. Weight reduction, specifically through utilizing aluminium alloys to replace steels, has become a major interest in this area. A 40% reduction in weight and 30% reduction in fuel consumption can be achieved by using aluminium alloys [1]. However, their poor ductility at room temperature restricts the widespread adoption. The most common solution to this problem is forming the alloys at elevated temperatures, e.g. using warm or hot stamping processes.

In hot stamping process, the high post-form strength potential of aluminium alloys is largely influenced by the quenching rate during the in-die quenching stage of the process [2]. The interfacial heat transfer coefficient (IHTC) is an important thermo-physical parameter characterizing the heat exchange between the blank and the forming tools. Hence, it has been widely used in both Finite Element (FE) modelling of hot forming processes and forming process parameter determination [3]. Although many studies have been conducted on the IHTC in hot forming of high strength steel [4], very few focus on hot forming of aluminium alloys, especially with different die materials. In this work, the IHTC between the aluminium alloy AA7075-T6 and two different die materials, cast iron and H13 die steel, was determined through hot stamping tests and simulations, under different contact pressures up to 17 MPa.

2. Methodology

2.1. Experiment setup



The experiments were conducted on a dedicated test rig, the IHTC-Mate, which was integrated on a Gleeble 3800 thermo mechanical simulator. The aluminium alloy AA7075-T6, a high strength alloy widely utilized in the aviation industry, was used in this study. The dimensions of the specimen were 120 mm × 10 mm with a thickness of 2 mm, while the dimensions of the contact surfaces of the die and punch were 500 mm × 250 mm. The specimen was heated by direct resistance heating, while the sliding block on the frame where the blankholders were mounted was made up of insulating material to isolate the specimen and blankholders from the rest of the rig. For each test, the heating rate, target temperature and the contact pressure in the form of the punch force were set in advance. The specimen was heated up to 490°C with a heating rate of 10°C/s and immediately quenched after the target temperature was reached. In the quenching stage, the punch moved towards the specimen and compressed it against the die, holding it with the pre-set punch force for 10 seconds, to simulate the same process that occurs during hot stamping. The hot stamping tests were carried out at a series of contact pressures from 0 MPa to 17 MPa on the two sets of die and punch respectively. A thermocouple embedded at the centre of the test specimen provided the temperature measurement and feedback control. Another two thermocouples were inserted into the punch and blankholder and connected to a data logger. The temperature evolution was used for the calibration of the developed FE model. The surface roughness (R_a) of the die and punch were measured using a White Light Interferometry equipment (Wyko NT9100).

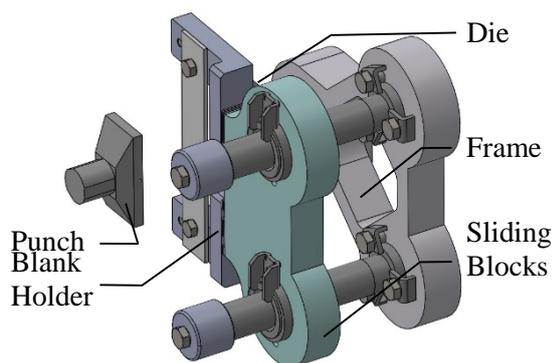


Figure 1. Structure of the dedicated test rig

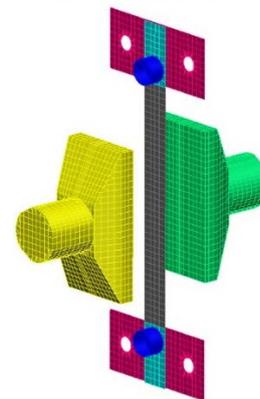


Figure 2. FE simulation model for IHTC determination

2.2. FE simulation

The FE model of the test rig was created using the commercial simulation software PAM-STAMP, as shown in Figure 2. The geometry of the blank, punch, die and blank holders generated in Solidworks were imported into PAM-STAMP and the material properties of all the parts and the process parameters were kept consistent with those used in the experiments. Within the temperature range used in the tests, the average thermal conductivities of cast iron and H13 die steel were 44.0 W/m-K and 24.4 W/m-K respectively. The initial temperature of the specimens was set to 490°C at the middle segment. The initial temperature of the die and punch were set to 30°C.

2.3. Determination of the IHTC values

Through assigning a series of IHTC values between the hot blank and the cold die and punch in PAM-STAMP, different temperature evolutions of the node at the specimen's centre during quenching were plotted and compared with the temperature evolution recorded by the data logger during the experiment on the same figure. The IHTC value and corresponding simulated temperature evolution that showed

the best fitting to the experimental results was determined to be the IHTC value in the experiment. As shown in Figure 3, the IHTC value between the hot blank and cast iron was found to be 13.5 kW/m²K for a contact pressure of 5 MPa, which provides the best fit to the experimental results.

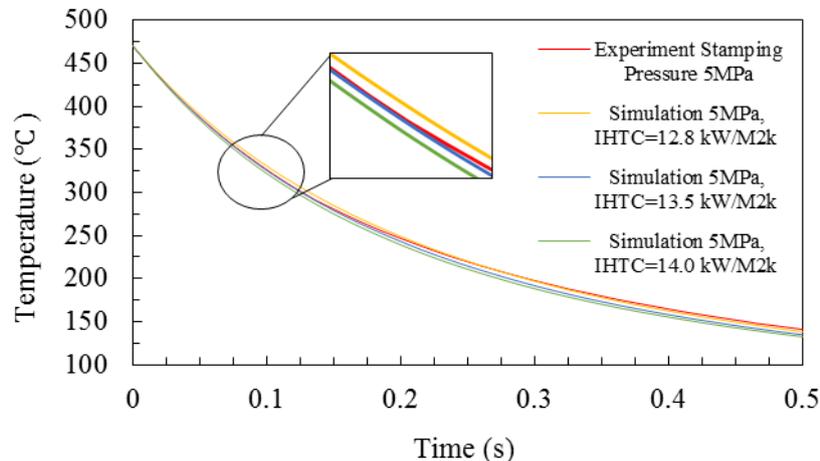


Figure 3. Temperature evolution of specimens centre with cast iron die with various pre-defined IHTC values

3. Results and discussion

Figure 4 shows that an increase in contact pressure promotes a significantly higher IHTC value within a certain pressure range. For cast iron, there is a remarkable growth of the IHTC value from 0.8 kW/m²K at zero contact pressure to 15 kW/m²K at a contact pressure of 13 MPa, after which a plateau in the IHTC value was observed. Similar to the trend of the IHTC for cast iron at different contact pressures, the IHTC for H13 die steel increased with increasing contact pressure from 0 MPa to 10 MPa, and subsequently plateaued at approximately 8.4 kW/m²K. Higher contact pressures lead to more deformation of the asperities on the workpiece material, leading to a sharp increase in the real contact area and thus an enhanced thermal exchange, resulting in an increase in the IHTC [5]. As the real contact area approached the apparent contact area under high pressure, convergence in the IHTC value was observed. Additionally, the results suggest that thermal conductivity and surface roughness, which were different for both materials, have appreciable effects on the IHTC, which has been confirmed by previous research [6, 7].

According to research on continuous cooling transformation diagrams (CCT) of aluminium alloys [8], when the quenching rate in a forming process is lower than the alloy specific critical cooling rate, there is a tendency for some solute elements to precipitate out as coarse particles, which weakens the alloys' response to any subsequent artificial ageing. In general, AA7XXX alloys require a higher quenching rate (over 50°C/s) while AA6XXX alloys' critical quenching rate is approximately 20°C/s. For the same alloy grade, the critical quenching rate is also alloying element dependent, i.e. the higher the content of alloying elements, the greater quenching rate that will be required. By superimposing the quenching curves with the CCT diagrams, the required contact pressure for achieving the critical quenching rate for any aluminium alloy can be determined. The converged value of the IHTC determined from the experiments would also prevent an excessive contact pressure from being applied that would have no effect on the IHTC, reducing tool wear, and promoting the cost efficiency of the hot stamping process.

During the quenching stage of the hot stamping process, the hot aluminum blank is rapidly cooled down by cold dies with embedded water cooling channels. Within the typical contact pressure range encountered in aluminium alloy hot forming processes, the increase in the IHTC for cast iron is almost double that of the increase in the IHTC for H13 die steel as the contact pressure is increased, resulting

in a much higher quenching rate. For a component with large dimensions and a complex geometry, the temperature distribution over the surface may be preferred to be uniform or tailored during the forming and quenching process in order to achieve the desired strength and thickness distribution [9], and this may be controlled by utilizing different die materials in different parts of the forming tool and with different contact pressures applied. By using cast iron, the design of the cooling channels may be more flexible, enabling more effective and efficient quenching, compared with conventional H13 tools in which cooling channels would need to be drilled during manufacturing. Utilizing different materials may also be beneficial for hot forming processes where blankholders are used, as they usually result in a faster than required temperature drop and premature cracking in their contact region as the central portion of the component is being formed.

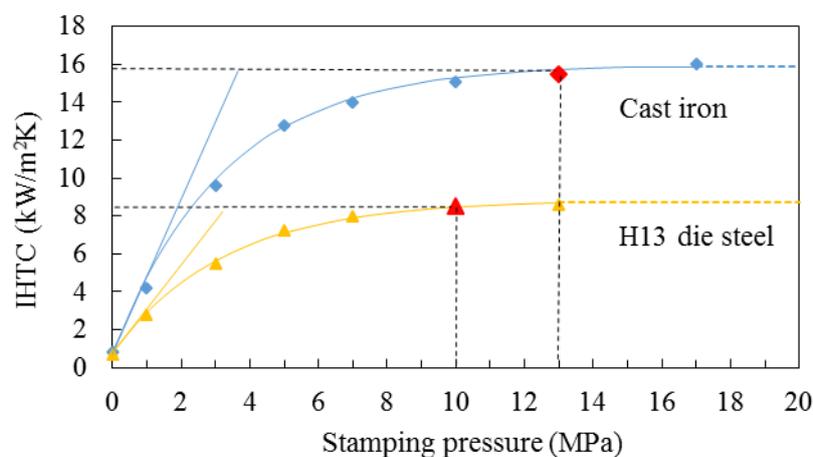


Figure 4. Effect of contact pressure on the IHTC with different die materials

4. Conclusion

In this work, the interfacial heat transfer coefficient (IHTC) between a hot aluminium alloy 7075-T6 blank and two die materials, cast iron and H13 die steel, were investigated based on hot stamping experiments in conjunction with FE simulations in PAM-STAMP. IHTC values under a series of different contact pressures were obtained, it was found that the IHTC increased with increasing contact pressure up to a plateau value. For cast iron, the IHTC converged to a value of 15 kW/m²K when the contact pressure was higher than 13 MPa. For H13 die steel, the IHTC plateaued at 8.4 kW/m²K at a contact pressure of 10 MPa. From the results, it can be deduced that cast iron forming tools might be more advantageous for manufacturing ultra-high strength lightweight components from AA7XXX alloys or quenching rate sensitive alloys, while H13 steel might be more suitable for manufacturing blankholders or forming aluminum alloys that are less quenching rate sensitive.

References

- [1] LUTSEY N P 2010 *Institute of Transportation Studies Report* UC Davis
- [2] MARTIN J W 1998 *Precipitation Hardening 2nd ed* (Britis: Butterworth Heinemann) pp79-124
- [3] Bai Q *et al* 2012 *Int. J. of Machine Tools and Manufacture* **56** 102
- [4] Caron E *et al* 2014 *Int. J. of Heat and Mass Transfer* **71** 396
- [5] Chang Y *et al* 2016 *J of Material Processing Technology* **228** 25
- [6] Kreith F *et al* 2011 *Principle of Heat Transfer 7th ed* (USA: CENGAGE Learning) pp 23-45
- [7] Holman J P *et al* 2010 *Heat Transfer 10th ed* (USA: McGraw Hill) chapter 1 pp5-9
- [8] Milkereit B *et al* 2012 *Material Sci. and Eng. A* **550** 87
- [9] Karbasian H *et al* 2010 *J of Material Processing Technology* 210 pp 2103-2118