Available online at www.sciencedirect.com

ScienceDirect

materialstoday: PROCEEDINGS

ELSEVIER

Materials Today: Proceedings 2S (2015) S434 – S439

Joint 3rd UK-China Steel Research Forum & 15th CMA-UK Conference on Materials Science and Engineering

# Determination of heat transfer coefficient for hot stamping process

Kang Ji, Omer El Fakir, Haoxiang Gao, Liliang Wang*

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

**Abstract**

The selection of the heat transfer coefficient is one of the most important factors that determine the reliability of FE simulation results of a hot stamping process, in which the formed component is held within cold dies until fully quenched. The quenching process could take up to 10 seconds. In order to maximise the production rate, the optimised quenching parameters should be identified to achieve the highest possible quenching rate and to reduce the quenching time. For this purpose, a novel-testing rig for the Gleeble 3800 thermo-mechanical simulator was designed and manufactured, with an advanced control system for temperature and contact pressure. The effect of contact pressure on the heat transfer coefficient was studied. The findings of this research will provide useful guidelines for the selection of the heat transfer coefficient in simulations of hot stamping processes and useful information for the design of hot stamping processes.



*Keywords:* Aluminium alloy; hot stamping; interfacial heat transfer coefficient; automotive; light-weighting

## 1. Introduction

The ever increasing demand for more fuel-efficient vehicles to reduce energy consumption and air pollution is a challenge for the automotive industry. Light-weighting is one of the most effective approaches to improve fuel

* Corresponding author. Tel.: +44 (0)20 7594 3648.
*E-mail address:* liliang.wang@imperial.ac.uk


doi:10.1016/j.matpr.2015.05.059

economy and to reduce $CO_2$ emission of vehicles. This has been demonstrated by many vehicle mass reduction programs worldwide. Studies have shown that every 10% reduction in vehicle weight can result in a 6-8% improvement in fuel efficiency [1-3]. This means that every 100kg weight reduction results in a $CO_2$ reduction of up to 12.5g$CO_2$/km driven over the entire vehicle life. In addition to such primary benefits, vehicle light weighting reduces the power required for acceleration and braking, which provides the opportunity for secondary weight reduction by the employment of smaller engines, transmissions and braking systems. Of the existing engineering materials used in the automotive industry, aluminum alloys are ideal candidates to replace heavier materials (e.g. steel and copper) in cars to achieve weight reduction. It has been found that every kg of aluminum, which replaces 2kg of steel, can lead to a net reduction of 10 kg of $CO_2$ equivalent over the average lifetime of a vehicle [2, 3]. However, poor formability at room temperature is one of the most significant impediments to the application of aluminum alloys in vehicles, especially those grades with medium or high strength. Therefore, over the years, great efforts have been made to improve the formability of aluminum alloys by developing new alloys with higher ductility [4-6], or advanced forming technologies to achieve higher formability. Of the existing forming technologies, superplastic forming [7-9], warm forming [5,10] and hot stamping [11-14] can be used to form aluminum components of complex shapes.

Hot stamping is one of the most promising forming technologies for the mass production of complex shaped aluminum panel components because of many attractive features, including high complexity geometry, high post-form strength, high productivity and low cost. One of the key features of the hot stamping technology is to use cold dies to form a hot blank, so that quenching and forming within the cold dies can be realized simultaneously. Therefore, the interfacial heat transfer coefficient (IHTC) is of great importance for this technology, which determines the forming and quenching time, i.e. the production rate. Moreover, the critical quenching rate must be achieved for a heat treatable aluminum alloy to ensure optimized post-form strength.

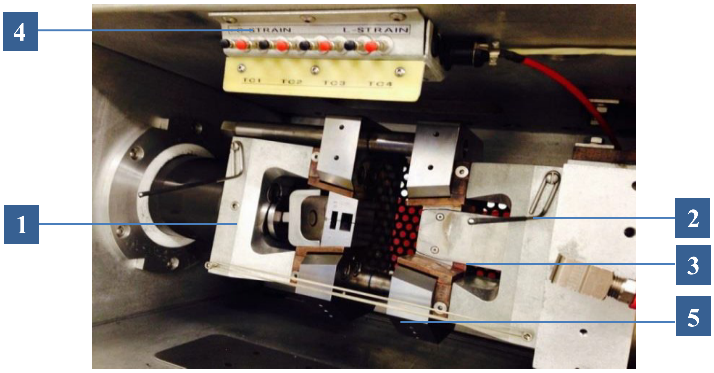
Due to the complex thermo-mechanical nature of the hot stamping technology, there is no dedicated equipment available yet to reproduce this forming process and to characterize the interfacial heat transfer coefficient for this technology. In the present research, heat transfer coefficient testing equipment was developed and integrated with a Gleeble 3800 thermo-mechanical simulator, and the effects of contact pressure on the heat transfer coefficients between the forming tool and an aluminum alloy (AA5754) have been determined and studied.

## 2. Development of heat transfer coefficient testing equipment for hot stamping process

Hot stamping is a complex thermo-mechanical forming process, which involves a solution heat treatment (SHT) stage (within a furnace), a forming and quenching stage (within cold dies), and an ageing stage (within a furnace); the forming and quenching stage is key. The hot Al blank is transferred from a furnace to the forming tool quickly, where air cooling occurs, followed by forming and quenching within cold dies. The whole process is normally finished within 20s, and most of the heat in the Al blank is transferred to the cold dies via interfacial heat transfer. An interfacial heat transfer coefficient test rig was developed to measure the IHTC value for such a hot stamping process. IHTC is defined by:

$$IHTC = \frac{Q}{T_{workpiece} - T_{die}} \quad (1)$$

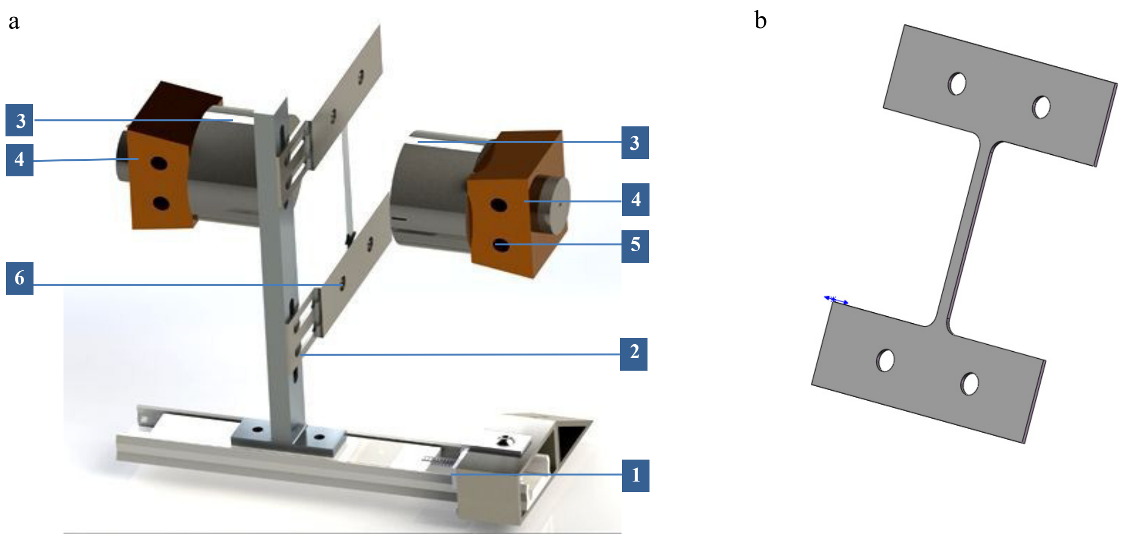
where Q is the total heat energy transferred from the hot workpiece to the cold dies, $T_{workpiece}$ is the initial temperature of the workpiece, and $T_{die}$ is the initial temperature of the die surface.




1 Left arm
2 Right arm
3 Space for test rig
4 Thermocouple data input
5 Screw holes

Fig. 1. Inner view of Gleeble chamber

This test rig was designed for the Gleeble 3800 system. The Gleeble 3800 can be used for conducting both thermal and mechanical tests that are controlled by its own software, QuickSim2. It was chosen on the basis of 6 main advantages. Firstly, the Gleeble can heat samples at a very high rate of 10,000˚C/s maximum, and it can also supply a high cooling rate with an air or water quench system. Secondly, tests can be totally controlled by the computer and include any reasonable change of loading or temperature during the test, and so can be designed to simulate the real production process accurately. Thirdly, the mechanical system of the Gleeble is able to exert a maximum of 20 tons of static compressive force, which is sufficient for the IHTC tests. Fourthly, the Gleeble has a thermal and mechanical control system with feedback available from thermocouples, transducers, load cells and a laser extensometer.  Fifthly, the signal delay from these is negligible, and so the accuracy of the whole system is high. Lastly, tests can be conducted in vacuum.




1 Slider
2 Workpiece supporter
3 Left and right dies
4 Left and right grips
5 M8 screw holes
6 Workpiece

Fig. 2. (a) Designed test rig; (b) workpiece

The inner view of the Gleeble test chamber is shown in Fig. 1. There are five important parts highlighted for this test: the left arm, which moves horizontally and applies a compression force; the non-movable right arm; the available space for the test rig; the thermocouple wire input ports that allow a maximum of four pairs of thermocouples to be connected, one of which is used for temperature feedback control; and the screw holes on the right arm.

The final designed test rig is shown in Fig. 2. It is assembled of 4 main parts: a slider, a workpiece supporter, left and right dies, and left and right grips.

The slider is shown as part 1 in Fig. 2(a). It is a two-part slider, and the inner part can move along and within the outer part. When there is no loading applied on the workpiece, a spring at the fixed end of the slider ensures that the workpiece does not contact the right die during heating. The slider is an important section that supports and fixes the whole system, while enabling uniaxial motion of the inner part.

The workpiece supporter is shown as part 2 in Fig. 2(a), and it can be divided into 3 parts: the central rod, upper bridge and lower bridge. The central rod is fixed on the inner part of the slider, and can move uniaxially. The functions of the two bridges are to position the workpiece, supply the holding force, and to conduct the electric current to the specimen.

The dies include the left die and the right die, represented by part 3 in Fig. 2(a). The left die works as a whole part and the right one is separated into two. One part of the right die is designed with a slot for holding thermocouples. 3 pairs of thermocouples can be used in the slot to determine the temperature history of the die. The thinner part of the right die is used for holding by the grips.

Grips (part 4 in Fig. 2(a)) are also in two parts, left and right, and each is further divided into two halves. The M8 screw holes (5 in Fig. 2(a)) on the grips are used to connect and fasten the wires to pass current from the Gleeble machine to the workpiece, and the inner curve surface is in contact with the thinner part of the dies to position and hold them to apply the compressive force.

The workpiece is designed as part 6 in Fig. 2(a) and Fig. 2(b). The wider area is fastened to the two bridges of the supporter for positioning, and the thinner area is the main test zone. The workpiece is heated to its SHT temperature first. The left die then moves and compresses the workpiece at its thinner section against the right die for 10 seconds, to simulate the forming and quenching stages in a hot stamping process. The loading condition and temperature history of the workpiece are recorded by a load cell and thermocouples respectively, and output to the computer.

## 3. Simulation for Quenching stage of hot stamping

A finite element (FE) model was developed in the commercial FE code ABAQUS, with 3D geometry files imported from Solidworks. The simulation parameters are identical to those used in the heat transfer tests, while the IHTC is the only adjustable parameter through the assignment of different heat transfer coefficient values to the die-workpiece interface. The element type and mesh refinement used in the model were determined through convergence studies. The material properties and conductivity were introduced as being temperature dependent. The workpiece is first heated to the SHT temperature, and then compressed by the two cold dies to be quenched, which is the same process as the experiment. Fig. 3(a) shows a simulation of the quenching process.

The nodal temperature histories of the workpiece at the positions corresponding to the embedded thermocouples attached to the workpiece and dies during the experiments are extracted and plotted in post simulation data processing. Temperature history curves of simulation results at different IHTC values varying from 1 to $9kW/m^2K$ are shown in Fig. 3(b), and the IHTC value of the best fitted curve to the experimental results is determined as the IHTC value for that contact pressure. A higher IHTC value led to a faster heat transfer, and if the value is high enough, the quenching time can be reduced to 1 second.

## 4. Experiments and results

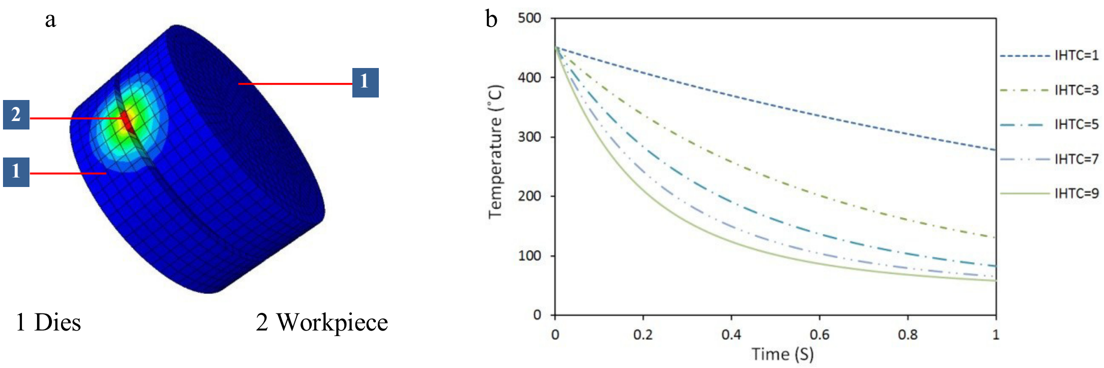



Fig.. 3. (a) FE Simulation of quenching process; (b) temperature history curves of simulation results at different IHTC

Heat transfer coefficient tests have been conducted under a wide range of contact pressures of 10, 20, 50, 100 and 200 MPa, although the contact pressure during hot stamping is normally below 50 MPa. The recorded temperature histories at 50 and 100 MPa are shown in Figs. 4 (a) and (b). At 50 MPa contact pressure, strong oscillations were observed at the initial contact and thus only the lower temperature region is presented. The simulated results of 2.5kW/m$^2$K agreed well with the experimental results and hence the heat transfer coefficient was identified correspondingly. The temperature history curve of experimental data and simulation results are also compared for a contact pressure of 100 MPa and a interfacial heat transfer coefficient of 12 kW/m$^2$K was identified.

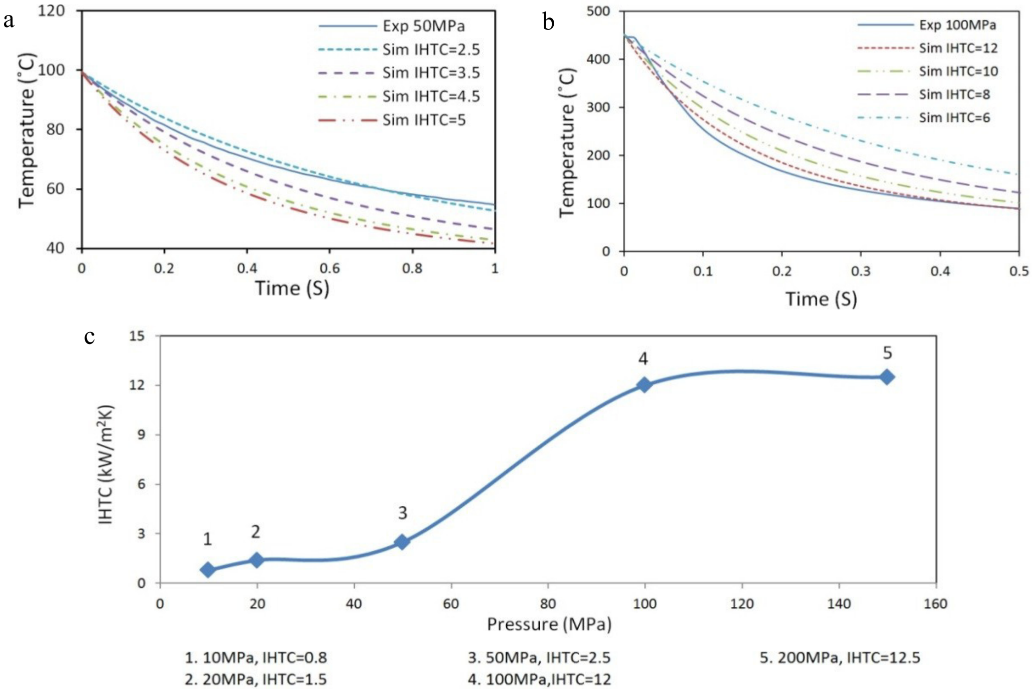



Fig. 4. (a) Experimental curve at 50MPa with fitted simulation curves; (b) Experimental curve at 100MPa with fitted simulation curve; (c) IHTC-Pressure curve

Experimental temperature histories under contact pressures of 10MPa, 20MPa, 50MPa, 100MPa and 200MPa have been fitted to the simulation results to study the effect of contact pressure on the heat transfer coefficient. The resulting IHTC-Pressure curve is shown in Fig. 4(c). The IHTC value goes up with increasing pressure from 50MPa to 100MPa, and reaches its peak value of around $12kW/m^2K$ above 100MPa. The gentle increase in the heat transfer coefficient is followed by a plateau. This is due to the increase of the real contact area with increasing contact pressure. The real contact area is the area where the atoms of one surface contact the atoms of the other surface. Since the heat transfer between the Al workpiece and die steel is realized through real contact area rather than the apparent contact area, at low contact pressure condition, the real contact area is low, leading to a low value of heat transfer coefficient. As the contact pressure increases, the real contact area increases correspondingly leading to a gentle increase in heat transfer coefficient. When the contact pressure was above a critical value, 100 MPa in the present research, the real contact area is close to the apparent area, leading to a constant heat transfer coefficient.

## 5. Conclusion

In the present research, heat transfer coefficient testing equipment was developed for a hot stamping process. The temperature history of the workpiece representing the hot stamping process was accurately reproduced and recorded by the tester. By using a reverse modelling technique, the heat transfer coefficient for the hot stamping process was determined. It was found that the heat transfer coefficient increases with increasing contact pressure, and a maximum value of $12kW/m^2K$ can be observed when the contact pressure is above 100MPa for this AA5754 sheet material under these test conditions.

## Acknowledgements

The authors would like to thank the undergraduate students Mr Yang Wang, Mr Haomiao Fang, Mr Tianyang He and Mr Xiaorong Shan for their kind help and efforts on this paper.

## References

[1] R. Inc., Impact of Vehicle Weight Reduction on Fuel Economy for Various Vehicle Architectures, in, 2008.
[2] B.L. Mordike, T. Ebert, Magnesium: Properties - applications - potential, Materials Science and Engineering: A, 302 (2001) 37-45.
[3] C.A. Ungureanu, Das, S., Jawahir, I.S.,, Life-cycle Cost Analysis: Aluminum versus Steel in Passenger Cars, in: W.Y. Subodh K. Das (Ed.) TMS (The Minerals, Metals & Materials Society), 2007.
[4] W.S. Miller, L. Zhuang, J. Bottema, A.J. Wittebrood, P. De Smet, A. Haszler, A. Vieregge, Recent development in aluminium alloys for the automotive industry, Materials Science and Engineering A, 280 (2000) 37-49.
[5] S. Toros, F. Ozturk, I. Kacar, Review of warm forming of aluminum-magnesium alloys, Journal of materials processing technology, 207 (2008) 1-12.
[6] S. Ji, D. Watson, Z. Fan, M. White, Development of a super ductile diecast Al–Mg–Si alloy, Materials Science and Engineering: A, 556 (2012) 824-833.
[7] J. Lin, Selection of material models for predicting necking in superplastic forming, International Journal of Plasticity, 19 (2003) 469-481.
[8] A.J. Barnes, Superplastic forming 40 years and still growing, J. Mater. Eng. Perform., 16 (2007) 440-454.
[9] T.G. Langdon, Seventy-five years of superplasticity: historic developments and new opportunities, Journal of materials science, 44 (2009) 5998-6010.
[10] D.M. Li, A. Ghosh, Tensile deformation behavior of aluminum alloys at warm forming temperatures, Mater. Sci. Eng. A-Struct. Mater. Prop. Microstruct. Process., 352 (2003) 279-286.
[11] O. El Fakir, S. Chen, L.L. Wang, D. Balint, J.P. Dear, J.G. Lin, Numerical investigation on the hot forming and cold-die quenching of an aluminium-magnesium alloy into a complex component, Materials Science Forum, 765 (2013) 368-372.
[12] L. Wang, J. Lin, O. El Fakir, A. Foster, G. Adam, J. Sellors, HFQ forming: a novel lightweight sheet metal forming technology for mass-production, in: TTP2013 Tools and Technologies for Processing Ultra High Strength Materials., Austria, Graz., 2013.
[13] L. Wang, M. Strangwood, D. Balint, J. Lin, T.A. Dean, Formability and failure mechanisms of AA2024 under hot forming conditions, Materials Science and Engineering A, 528 (2011) 2648-2656.
[14] O. El Fakir, L. Wang, D. Balint, J.P. Dear, J. Lin, T.A. Dean, Numerical study of the solution heat treatment, forming, and in-die quenching (HFQ) process on AA5754, International Journal of Machine Tools and Manufacture, 87 (2014) 39-48.