DEVELOPMENT OF A TEST SETUP FOR THE EXPERIMENTAL DETERMINATION OF THE HEAT TRANSFER COEFFICIENT FOR COMPOUND FORGING

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Abstract

In numerical process design, the heat transfer coefficient (HTC) is used to calculate the intensity of heat transfer at an interface, for example between dies and workpiece. In most finite element calculations for bulk metal forging, a constant HTC is currently assumed, as there is no complete understanding of the relationship between the heat transfer coefficient and its influencing variables (e.g. contact pressure or temperature), which leads to inaccuracies in the simulation results. However, specifically set temperature profiles are necessary, particularly in the compound forging of aluminum and steel, in order to adjust the forming properties of the dissimilar semi-finished products. Setting the incorrect boundary conditions in the compound forging processcan lead to temperature profiles that cause the aluminum semi-finished product to melt or to insufficient formability of the steel. Due to the required temperature difference in the compound forging process of dissimilar materials, the accurate modelling of the heat transfer coefficient is of particular importance in the process design. However, the investigation of the HTC in forging processes represents a major challenge from an experimental point of view due to the very short pressure contact times and the high heating rates that occur. According to the current state of the art, there is no method for determining the prevailing HTC within a compound forging process as a function of relevant effective variables such as pressure, temperature or lubrication with reasonable effort.

This paper presents a new test setup for recording HTC for the compound forging of aluminum and steel. In addition to the first prototype of the test setup, the test materials EN AW-6082 and S235JR were investigated with regard to their plastic behaviour and their thermally induced elongation. These material properties are used to define process windows for compound forging as well as for joint heating.

Keywords: Heat transfer coefficient, compound forging, process design, EN AW-6082, S235JR

1. INTRODUCTION

One effective way for car manufacturers to reduce CO_2 emissions is to reduce the weight of the vehicle. While lightweight construction solutions using hybrid components are already advanced in sheet metal forming, they are not yet particularly well represented in the forging process chain. At the same time, the weight proportion of bulk metal formed components in cars is almost as high as that of sheet metal parts. In this context, new process developments, such as compound forging, can offer even more opportunities for lightweight construction solutions and therefore have the potential for even greater weight reduction in the future [1]. Compound forging enables the combination the advantages of different materials in one component and thus achieving a component design that is optimised for the occuring loads. The production of solid-formed hybrid components offers the possibility of producing ready-to-install and requirement-optimised hybrid parts in a few process steps in a resource-saving manner. A joint between the individual materials is created in the forming process by means of a shape and material bond. The process design of a compound forging process is complicated, as the materials have different flow properties and thus have to be heated to different materialspecific forming temperatures in order to achieve more uniform flow properties [2]. Wohletz and Groche joined cylinders made of steel and aluminium (C15/AW-6082) by full forward and cup extrusion and investigated the influence of temperature on the joint [3]. It was found that oxide layers which are formed at elevated forming temperatures have a negative influence on the quality of the final interface. Essa et al. investigated the forming behaviour during upsetting of hybrid steel blanks for a core made of a soft steel (C15E) in combination with a shell made of stronger steel (C45E) [4]. In subsequent work, hybrid gears were produced by die forging. The inner part of the gear was made of aluminium and the outer casing of steel [5]. Behrens and Kosch investigated the compound forging of steel and aluminium with regard to the temperature gradient between the joining partners and the influence of the alloy composition on the intermetallic joining zone [2]. Based on the knowledge gained, hybrid gears made of steel and aluminium were successfully manufactured. Further successful examples of compound forging were shown by Hänisch et al. in the combination of sheet metal and bulk specimens using impact extrusion and forging [6]. Compound forging of dissimilar materials poses a challenge with regard to the different forming temperatures of the materials. This is due to the fact that the temperatures present at the contact surfaces of the semi-finished products have a significant influence on the forming result and the formation of intermetallic phases. During the compound forging of semi-finished steel and aluminium products, the heat released from the higher-temperature steel might melt the aluminium locally when the solidus temperature is exceeded, which leads to gap formation and a reduction in strength. At the same time, the heat dissipation of the semi-finished steel product reduces its deformation capacity, which increases the risk of cracking. In addition, compound forging results in a heat flow from the semi-finished products towards the less heated die [2]. To summarise, it is necessary to identify the existing temperatures of the semi-finished products and tools in order to be able to numerically predict the forming result of the compound forging process more accurately. The heat transfer coefficient (HTC) is required to describe the heat transfer and the resulting temperatures in the numerical simulation. HTC that occurs between the contact pair under the existing influencing variables significantly determines the temperature within the inferface. The HTC is basically dependent on various time-variable process variables, such as the contact pressure and the surface temperature of the contact pair and the lubricating film thickness [7,8]. Fundamental investigations based on the indirect measurement method, experimental temperature measurement in the contact zone and numerical inverse variation of the HTC for the prediction of the measured temperature, were carried out, for example [9-11]. Barani et al. investigated the determination of the HTC for both the forging process and for the subsequent cooling lubrication. The HTC was determined for the forging process of a turbine blade using a temperature measurement in the forging die [9]. Caron et al. investigated the experimental recording of HTC in a press hardening process with the aid of thermocouples attached to the workpiece and die. The results of the thermocouples showed measurement inaccuracies, hence the HTC was determined using an inverse heat conduction algorithm [12]. Mendiguren et al. describe the experimental characterisation of the HTC for a press hardening process by varying the contact pressure and the mould temperature. It was shown that the HTC is primarily pressure-dependent and that the die base temperature has less influence on the heat transfer [13]. The state of the art shows that there is no test setup that allows the HTC to be recorded under controlled conditions. Instead, measurements were carried out in the process, where the boundary conditions cannot be controlled. In this work, a concept for a test setup was developed which allows the recording of the heat transfer in the form of the temperature change using different temperatures, contact pressures, lubricants and materials. The recorded temperature curves are then numerically determined inversely based on [12]. HTC for a hybrid compound forging process of EN AW-6082 and S235JR is to be determined in order to define process windows in which the production of hybrid components is possible. In the compound forging process, the aluminium cylinder is inserted into a steel tube and forged into a hybrid component. For this purpose, the flow behaviour of the materials and the coefficients of thermal expansion (CTE) were first determined experimentally to enable initial process windows to be defined. The tests for the HTC are carried out within these process windows once the test set-up has been commissioned.

2. MATERIAL AND METHODS

HTC should be investigated by varying the following effective variables such as contact pressure σ_N, workpiece temperatures T_{WP_steel}, $T_{WP\_aluminiuim}$, die temperature T_{die_steel}, and lubricant condition $\mu_{\text{lubricant}}$ see equation (1):

$$HTC = f\left(\sigma_N \left|T_{WP\_steel}\right|T_{WP\_aluminiuim}\left|T_{die\_steel}\right| \mu_{\text{lubricant}}\right) \quad (1)$$

The main requirements for the test setup are the ability to vary the contact pressure, the temperatures and the lubricant condition for different contact pairings. The test setup was designed for the Gleeble 3800 GTC thermo-mechanical forming simulator. **Figure 1(a)** schematically shows the developed test setup. Firstly, springs are pushed onto the guide pillars of the slide, followed by the frame into whose holes linear roller bearings are pressed and finally springs are pressed in again. On the right side there is a punch which is fixed, on the left side the punch is movable. Due to the floating bearing of the frame, it is always located in the center between the two punches. The specimen holders are mounted on the frame and hold the cylindrical specimen with a diameter of 20 mm. The current is applied to the specimen holder so that the specimen can be heated conductively. A thermocouple is welded to the specimen to measure and control the temperature. The specimen holders are thermally and electrically insulated from the frame by a ceramic plate. Thermocouples are welded to the punches in order to be able to measure the heating caused by contact with the heated specimen. Any combination of materials can be analyzed in the system with regard to heat transfer. In this case, the punch surfaces are made of steel S235JR and the test specimen of aluminum EN-AW6082 to simulate the contact state of the compound forging process under consideration. Contact conditions between the workpiece materials and the die can also be mapped by selecting the appropriate material for the punches and the test specimen.

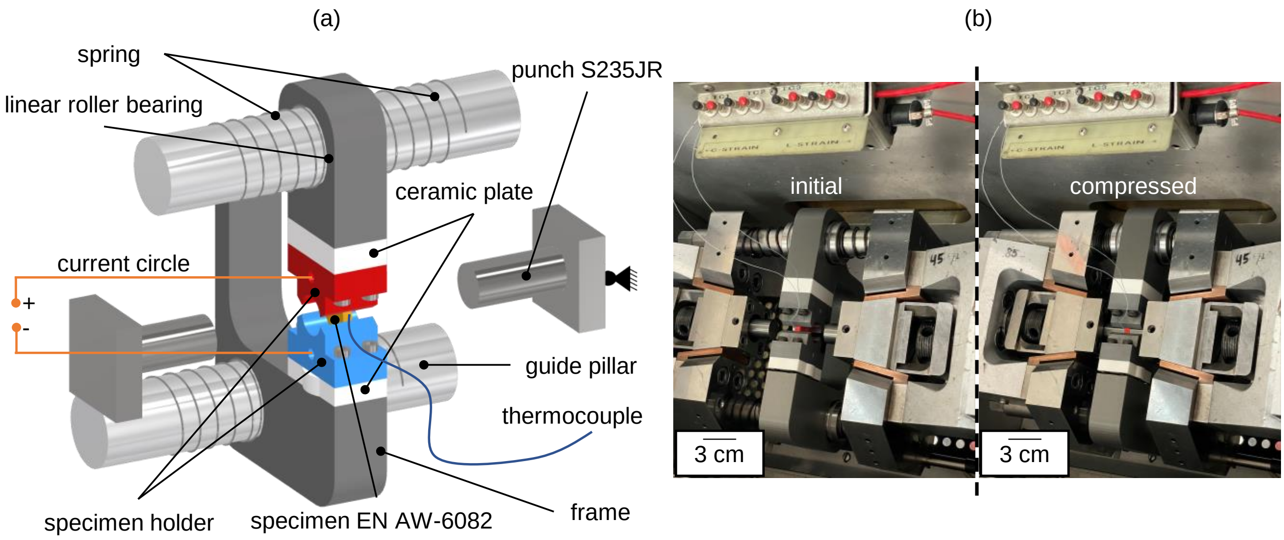

Figure 1 (a) Schematic test setup for recording the HTC, (b) first 3D-printed prototype in initial and compressed assembled state.

A prevailing vacuum environment in the measuring chamber is used to minimize heat losses due to heat transfer and dwell times. When the target temperature of the specimen is reached, a constant force is applied to the test specimen within the experiment via the left sliding punch and the fixed right punch. Uniform contact on both sides of the punches is realised by the floating bearing of the specimen through the spring system. A plastic deformation of the material is prevented by the specimen holders to enable the investigation of high contact pressures relevant for bulk metal forming without overlapping with other effects such as sliding friction. A first 3D-printed prototype is shown in **Figure 1(b)** with the floating bearing of the frame and the specimen holders. The prototype is used to analyse the functionality of the kinematics and the connection dimensions.

To record the CTE, cylindrical specimens with a diameter of 4 mm and a length of 10 mm were ground from the semi-finished steel and aluminum products. The specimens were welded with a type K thermocouple and mounted between two quartz tubes in the forming dilatometer. The quartz tubes hold the specimen and are at the same time used to measure the change in length of the specimens. During the test, the specimen is placed inside a copper coil which is used to heat the specimens inductively. A vacuum of $3{,}5E^{-3}$ mbar is induced before the test starts. The aluminum specimens were heated in 50 °C steps and held at each temperature for 60 s until the final temperature of 600 °C was reached. Steel specimens were heated in 100 °C steps and also held for 60 s at each temperature. The final temperature for the steel specimen was 1,200 °C. Throughout the test, the change in length of the specimen was recorded. Five repetitions were carried out for both materials.

The flow behaviour of aluminum and steel was determined using cylinder compression tests. **Table 1** lists the investigated test parameters, the specimen dimensions and the testing machine used. Each test was repeated five times under vacuum. The compression tests for steel were carried out on the Gleeble 3800 GTC forming simulator and heated conductively at a heating rate of 5 K/s and held at the target temperature for 60 s before upsetting. Due to the vertical structure and the conductive heating, a contact force of 0.3 kN must be applied so that the current flow for conductive heating can be realised. The cylinder compression tests of aluminum were carried out on the forming dilatometer as the application of the contact force would have resulted in a plastic deformation in the investigated temperature range.

Table 1 Test parameters of the cylinder compression tests for EN AW-6082 and S235JR

Material	Temperature (°C)	Strain rate (1/s)	Diameter (mm)	Length (mm)	Forming Simulator
EN AW-6082	300 I 350 I 400 I 450 I 500 I 550 I 600	0.1 I 1 I 20	5	10	Quenching and deformation dilatometer DIL 805A/D+T
S235JR	400 I 500 I 600 I 700 I 800 I 900 I 1,000	0.1 I 1 I 20	10	15	Forming simulator Gleeble 3800-GTC

3. RESULTS AND DISSCUSION

The results of the determination of the CTE are shown in **Figure 1(a,b)** for aluminum and steel. **Figure 1(a)** shows the temperature profiles used. The specimens were heated in 50 °C steps and held at the respective temperature for 60 s. The steel was tested up to 1,200 °C and the aluminum up to 600 °C. From the measured changes in length and the initial length of the specimen, the CTE was calculated over the test temperatures. The calculated CTEs are plotted against temperature in **Figure 1(b)**. Compared to steel, aluminum shows a CTE that is almost twice as high. The CTE initially falls and then rises continuously up to 550 °C and then falls again slightly. The drop may have been caused by the partially liquid phases in the aluminum, which can occur from approx. 570 °C. With steel, the CTE rises continuously as the temperature increases.

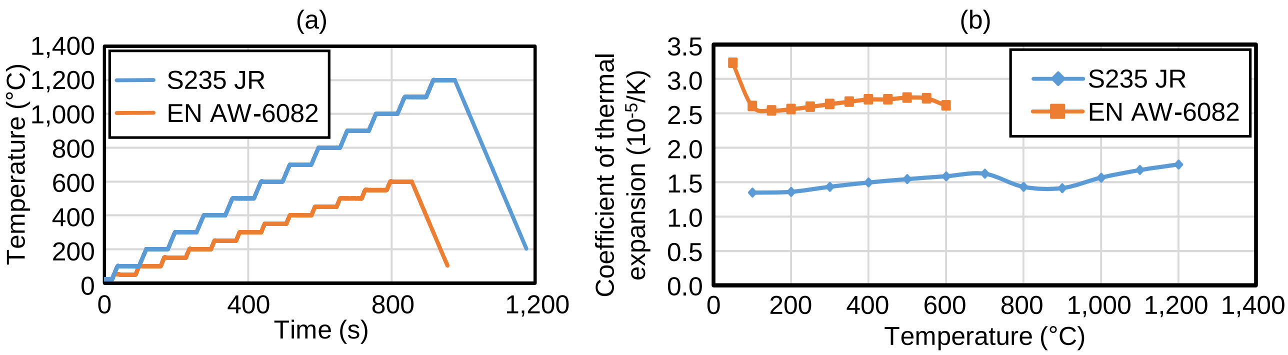

Figure 2 (a) Temperature profile for recording the CTE, (b) CTE for EN AW-6082 and S235JR.

Only in the range between 700 °C and 900 °C does a small drop occur, as the body-centred cubic (bcc) lattice of the ferrite transforms into the face-centred cubic (fcc) lattice of the austinite. Due to the lattice transformation from bcc to fcc, the packing density of the unit cell is increased so that the volume required for the atoms is reduced, resulting in the incidence in the CTE. The following two points can be derived from the results for the subsequent application of compound forging. Firstly, the aluminum will expand more during heating, which can be seen as a positive effect during heating, as this increases the contact between aluminum and steel. On the other hand, after forming, the aluminum will shrink more during cooling, so that there is a risk of cracking in the joining zone. It is therefore necessary to apply additional pressure during cooling or slow, controlled cooling is required to avoid damaging the bond created.

To determine the process window for compound forging, the flow behaviour of the two materials was determined. **Figure 3(a)** shows the flow curves for EN AW-6082. As the temperature increases, the flow stress decreases sharply, especially from 300 °C to 450 °C. From 450 °C to 550 °C, the reduction in flow stress flattens out as the temperature increases. As the strain rate increases, the flow stress also increases. The influence of the strain rate is more pronounced in the temperature range from 300 °C to 450 °C than at temperatures above 450 °C. A similar influence of temperature and strain rate can be observed for the analyzed S235JR, but the flow stress is much higher, see **Figure 3(b)**. At 400 °C and 500 °C, the steel still shows a hardening behaviour with an increase in the degree of deformation. Stronger hardening can be observed at these temperatures with an increased strain rate. The hardening continues to decrease as the temperature increases, which is reflected in a constant flow stress curve. Changes in the hardening behaviour are typical for steels in hot forming. For compound forging, the aim should be to achieve the same flow stress for both materials. In this case, the aluminum would have to be heated to 300 °C and the steel to at least 900 °C to achieve a flow stress of approx. 150 MPa. It is therefore essential to pursue an inhomogeneous heating strategy to prevent melting of the aluminum component

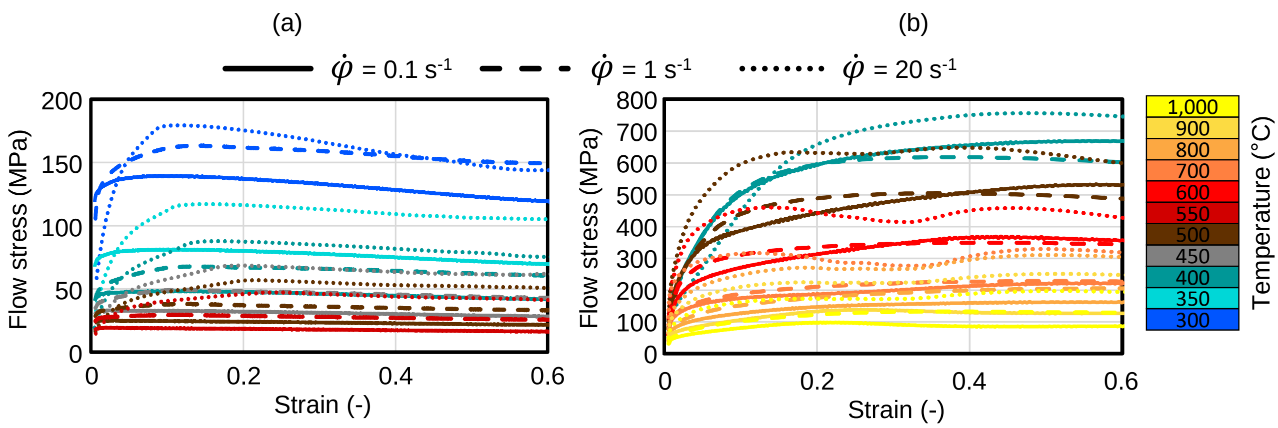

Figure 3 Flow curves for (a) EN AW-6062 and (b) S235JR.

4. CONCLUSION

The HTC is required for the design of the compound forging process in order to determine the necessary temperature distribution at which the forming is successful without melting the aluminum. In this work, a new experimental setup was presented that enables the determination of the HTC using an experimental-numerical approach. The temperatures in contact can be recorded under process-relevant conditions. The measured temperatures are then simulated in the digital twin of the experimental setup and the HTC is adjusted iteratively until the temperature curves match. Different contact pairings such as workpiece-workpiece or die-workpiece, as well as different contact pressures, temperatures and times can be investigated under controlled conditions as well as different lubrication conditions. The kinematics of the experiment were successfully tested using an initial prototype. For the subsequent investigations of the HTC, it is first necessary to determine the process window of the compound forging process. For this reason, the CTE and the flow behaviour were characterised for the materials EN AW-6082 and S235JR. The main findings indicate that the steel would have to be heated to 900 °C and the aluminum to 300 °C for forming with comparable flow stresses of approx. 150 MPa. There is a risk that the aluminum will melt if inhomogeneous heating is not provided. The following conclusions can be drawn from the results of the CTE for the compound forging process. Aluminum expands almost twice as much as steel. On the one hand, this is favourable for heating, as it increases the contact between the pre-joined semi-finished products. As the difference in expansion is also present during cooling, a slow, controlled cooling or cooling under pressure should be used to counteract the much more pronounces shrinkage of the aluminum. For future work, the prototype will be produced and initial tests will be carried out to record the temperature in the contact zone, which will be used to iteratively determine the HTC for subsequent use in the numerical model of the compound forging process.

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