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Influence of surface pressure and tool materials on contact heating of aluminum

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Abstract. The implementation of lightweight design concepts can significantly benefit from using highly efficient heating technologies such as contact heating in thermo-mechanical processing of sheet metal components. The investigation of the influence of surface pressure and tool material on the heating time and the heating rate during contact heating is the subject of this publication. A specially manufactured contact heating tool with comprehensive temperature and force measurement was used for studying the effects of different contact plate materials (CuZn39Pb3 and CuCr1Zr), surface pressures (3 MPa - 15 MPa) and variable plate thicknesses (1.0 mm - 5.2 mm) during heating of the aluminum alloy EN AW-7075 up to the solution heat treatment temperature of 475 °C. It was observed that heating time is lower for thinner workpieces. Furthermore, heating times decrease and heating rates increase significantly with increasing surface pressure for a pressure range of 3 MPa - 9 MPa. A further increase in surface pressure is not recommended, because the benefit in terms of further reduction of the heating time is marginal and the strength of the contact plate materials at elevated temperatures is limited. Contact heating using copper plates is significantly faster compared to brass plates and the conventionally used steel plates. Brass plates, however, benefit more from an increase in surface pressure. Both investigated materials allow faster heating than conventional steel plates due to their higher thermal conductivity. Depending on the specific process parameters the heating process can be accelerated to less than one second. Thus, contact heating can be realized within the press cycle.

Introduction

In modern manufacturing, the implementation of lightweight design concepts has been becoming more and more important in order e. g. to save resources in aviation [1], reduce fuel consumption and corresponding CO_2 emission in vehicles with conventional combustion machines [2], increase the range that an electrical vehicle can travel without recharging [3], or improve component function and user-friendlyness e. g. in medical engineering products [4]. These concepts involve design changes e. g. in order to realize integration of functions [5] and the use of typical lightweight materials such as high strength steel [6] or light-metal alloys [7]. These materials usually feature limited formability at room temperature so that forming of the complex geometries typically necessary for lightweight components frequently requires thermo-mechanical processes such as press hardening [8], quenching and partitioning [9], or superplastic forming [10]. In this context, fast and energy-efficient heating strategies are an essential prerequisite. Conventionally, the components are heated in roller hearth furnaces by means of thermal radiation. In practice, these furnaces reach lengths of up to 40 m [8] in order to achieve acceptable cycle times despite of the long furnace residence time. Alternative heating technologies requiring less investment costs and floor space and additionally allowing faster heating are based on resistive [11] and inductive heating [12]. However, resistive heating is efficient only for components with favorable - i. e. high

- ratio of length and cross section [13] and uniform heating for complex blank geometries is difficult for both - resistive and inductive heating [8]. Direct contact heating is a relatively new approach (suggested in [14]) with high potential to overcome these limitations. In this technology, the contact plates (typically made of metal or ceramics) that are heated by a heat source (e. g. induction coils [14], gas burners [15], cartridge heaters [16]) serve as energy storage and transfer the heat to the workpiece via thermal conduction. Compared to furnace heating, contact heating excels due to extremely high heating rates, which significantly reduces heating time [17]. The mechanism is very similar to the cooling in direct press hardening. From that process it is known that the heat transfer can be controlled by applying a defined contact force (contact pressure) [18, 19]. This suggests that the contact pressure is also a suitable parameter for adapting the heating rate in contact heating processes, which is e. g. relevant for thermo-mechanical processing of high-strength aluminum alloys [20]. Furthermore, it can be expected that different contact plate materials with significantly varying thermal properties (e. g. heat conduction coefficient) affect the heating rate in contact heating. However, neither the influence of surface pressure nor that of different contact plate materials on the heating behavior during contact heating have been investigated yet. Therefore, providing an analysis of these aspects is the aim of this paper.

Experimental Setup and Process Description

For this purpose, the contact plate tool shown in Fig. 1 was developed and mounted to a hydraulic press HS3-1500 by Dunkes with a press force of 1,000 - 15,000 kN. The setup consists of an insulation box that encases exchangeable contact plates, cooling plates and a gas pressure damper plate, that allows applying different surface pressures. This damper plate is coupled with a gas-pressure-based force measurement that enables recording the time-dependent surface pressure between the contact plates and the workpieces.

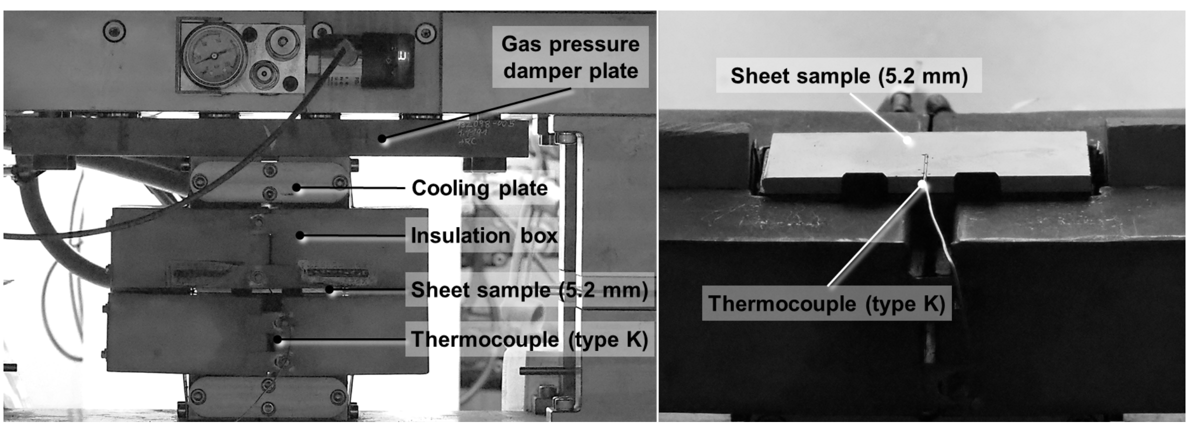

Fig. 1. Experimental setup: front view and view into the open tool with inserted sheet sample.

This study considers contact plates with a heating surface of 100 mm x 60 mm and a height of 35 mm made of the copper alloy CuCr1Zr and the brass alloy CuZn39Pb3, respectively (see Fig. 2). These materials feature approximately the same heat capacity and different thermal conductivity (see Table 1). Thus, the influence of the thermal conductivity of the contact plate material on the heating process can be investigated.

Fig. 2. Contact plates made of different materials.

Table 1. Thermal material properties of the contact plate materials and the workpiece material at room temperature.

	CuCr1Zr	CuZn39Pb3	EN AW-7075
heat capacity	383 J/kgK	377 J/kgK	862 J/kgK
thermal conductivity	330 W/mK	123 W/mK	145 W/mK

Both, the upper and the lower contact plate were heated with four individually controlled silicon nitride ceramic heating elements by Bach Resistor Ceramics GmbH. These heating elements feature rectangular geometry in order to facilitate homogeneous temperature distribution. The time-dependent temperatures of the contact plates were recorded using type K thermocouples by OMEGA with a sampling rate of 10 Hz during the tests. Furthermore, the pressure in the gas damping plate was measured and served as basis for determining the surface pressure acting on the contact plates and the workpieces to be heated, respectively.

The specimens considered in this study were made of EN AW-7075 with a width *w* of 60 mm, a length *l* of 100 mm and thicknesses *s* of 1.0 mm, 2.0 mm, 3.0 mm; 4.3 mm and 5.2 mm. In order to record the time-dependent temperature of the workpiece, rectangular grooves were milled into the specimens and thermocouples were inserted in the center of the specimen as shown in Fig. 3. For the sheets with 1.0 mm thickness thermocouples with a diameter *d* of 0.5 mm were used. For all other sheet thicknesses thermocouples with a diameter of 1 mm were used. The groove width was chosen corresponding to the width of the thermocouple. The groove depth amounts to the sum of half of the sheet thickness and half of the height of the thermocouple. Analogous to the temperature measurement of the contact plates also here type K thermocouples by OMEGA were used and the sampling rate was set to 10 Hz.

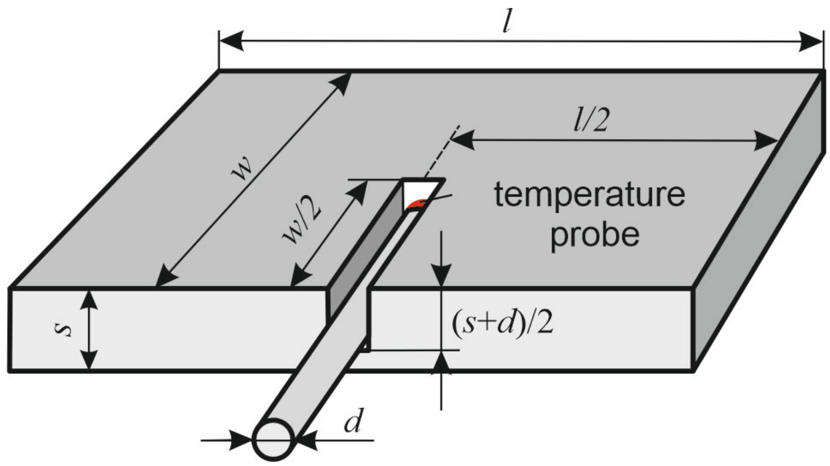

Fig. 3. Principal sketch of the sheet specimen for contact heating tests.

For the contact heating experiments, the contact plates were preheated for 15 minutes in order to achieve homogenous local temperature distribution. As it is known that the temperature rise in the workpiece is very quickly at the beginning of the process, but slows down as it approximates the temperature of the contact plates, the contact plate temperature is usually chosen higher than the target temperature of the workpiece. Here, the contact plates were pre-heated to 500°C in order to achieve the desired specimen temperature of 475°C - i. e. the solution heat treatment temperature of EN AW-7075 - in a reasonable timeframe. Then, a specimen was inserted, the tool was closed within approx. two seconds and a defined surface pressure between the contact plates and the specimen was applied by adjusting the pressure in the gas pressure damper plate correspondingly. For each sample thickness a test series was carried out by varying the surface pressure between 3 MPa and 15 MPa in steps of 3 MPa.

Fig. 4 shows an exemplary process diagram based on the measured time-dependent surface pressure between workpiece and contact plates and corresponding temperatures of workpiece and contact plates for a representative test using copper contact plates. At the moment t=0 s, the contact plates are closed, and the sheet specimen is heated from both sides. From this moment, the surface pressure rises approx. linearly up to the target value that is 9 MPa in the regarded case causing rapid heating of the aluminum specimen. At the same time, a temperature reduction of approx. 20 K of the contact plates can be observed as the heat is transferred into the specimen. Correspondingly, an increase of the workpiece temperature occurs. The measured temperature curve is characterized by an initial fast rise that decreases more and more when it approximates the temperature of the contact plates, which is in good agreement with [16]. After reaching the target temperature of 475°C, the test is completed, the specimen is removed from the tool and quenched in water, and the contact plate temperature is re-adjusted for next test of the test series.

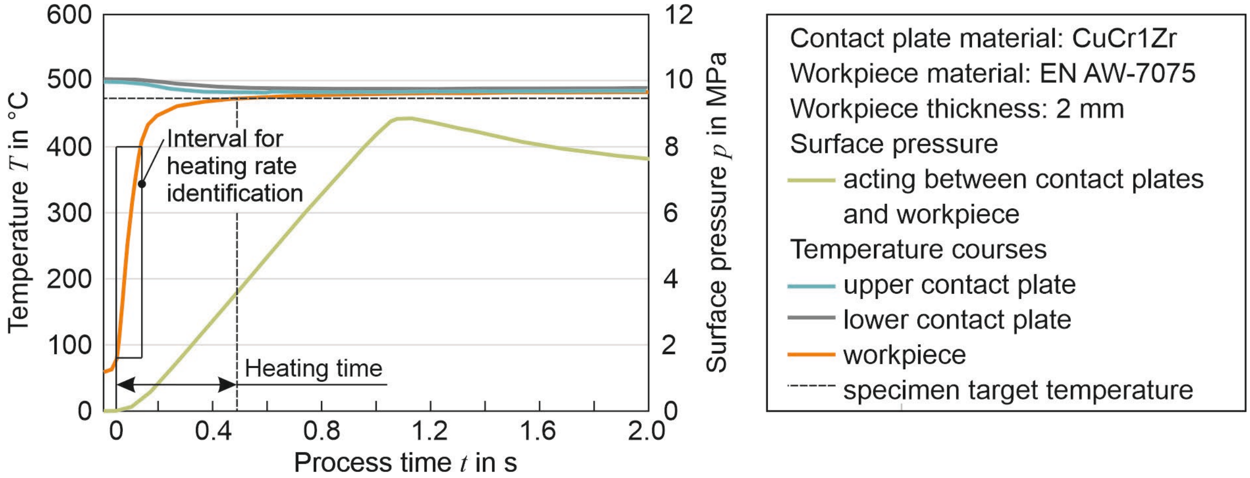

Fig. 4. Time-dependent surface pressure between workpiece and contact plates and corresponding temperatures of workpiece and contact plates.

Based on this measured data, two characteristic values were identified (see also Fig. 4):

1. The heating time t_{heat} was determined as the time interval between closing of the dies (t=0 s) and the moment when the specimen temperature reaches the target temperature of 475°C.
2. The maximum heating rate $\dot{T}$ was determined by referring the temperature difference to the corresponding time difference during the fast (and approximately linear) rise of the temperature. This value allows direct comparison to earlier experiments performed with standard contact plate materials presented in [17].

Influence of the Surface Pressure on the Heating of the Workpiece

Fig. 5 shows the heating times at different surface pressures for five different sheet thicknesses (1.0 mm - 5.2 mm). The contact plate material considered here is the copper alloy. The representative curves for all sheet thicknesses indicate that the heating time decreases with increasing surface pressure. However, the curves show that this effect is limited, because at surface pressures of 9.0 MPa and above higher surface pressures have hardly any further positive influence on the heating time, regardless of the sheet thickness to be heated. This suggests that at lower surface pressure the contact conditions are not ideal. This might be attributed to unevenness or roughness of the sheet. With increasing pressure these deficits are reduced and at a surface pressure of 9 MPa all unevenness or roughness is sufficiently leveled so that the contact conditions are almost constant for even higher pressure. Furthermore, the heating time decreases significantly with reduced sheet thickness. For example, the heating times at the maximum sheet thickness of 5.2 mm and a surface pressure of 3.0 MPa are approx. 13.1 s. With a sheet thickness of 1.0 mm, the heating time drops by approx. 86% to 1.8 s for the same surface pressure.

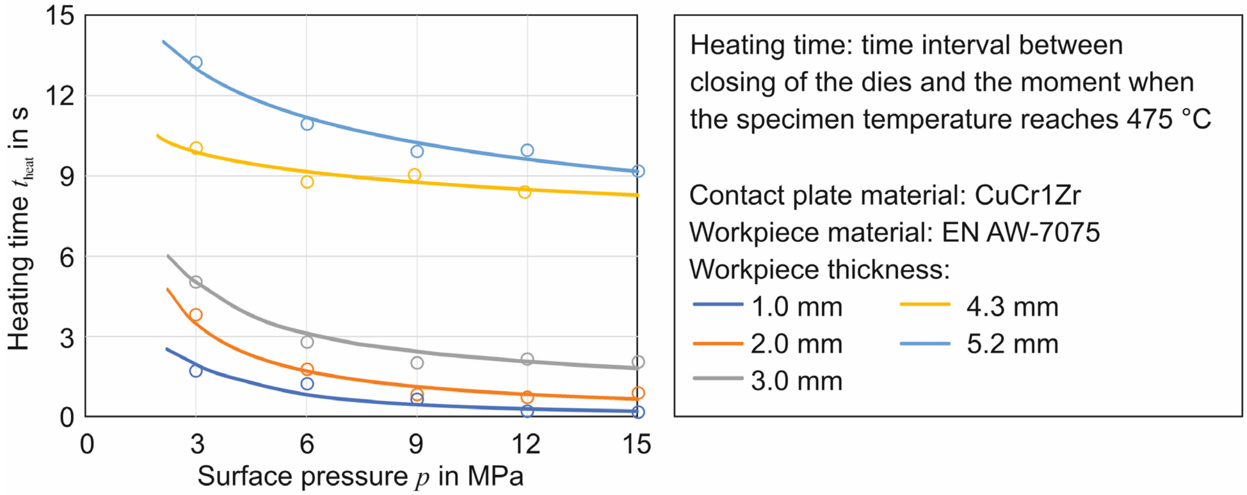

Fig. 5. Heating times for different thicknesses of the aluminum workpiece as function of the surface pressure.

Influence of the Contact Plate Material on The Heating of the Workpiece

In addition to investigating the influence of surface pressure, the material of the contact plates and its influence on the heating rates was studied. For this purpose, additional tests were done using contact plates made of brass alloy. The heating times at varying surface pressures for an exemplary sheet thickness of 2.0 mm are compared to those determined for the copper plates in Fig. 6. In principle, the curves show similar qualitative trends, but the heating times are in general higher in case of the brass plates. This effect can probably be attributed to the lower thermal conductivity of the brass compared to the copper alloy. This means specifically that also in case of heating with brass plates the heating time decreases with increasing surface pressure. The quantitative comparison of the curves determined for the two contact plate materials even shows that in case of heating with brass contact plates the influence of the surface pressure is higher than in case of heating with copper contact plates. For example, the heating under a surface pressure of 3.0 MPa takes more than 10.0 s if brass plates are used, while in case of copper plates such a high heating time was sufficient for heating significantly thicker sheets (see Fig. 5) and heating a sheet with a thickness of 2.0 mm required less than 3.8 seconds. However, also the drop of heating time with increasing surface pressure is more significant if brass plates are used. Already at 6.0 MPa surface pressure, only 4.8 s are required to reach the target temperature, which corresponds to a reduction of 48 %. This percentage reduction is comparable to that of the copper plates (1.9 s at 6.0 MPa). Altogether, the ratio of the heating times for the two contact plate materials (approx. 2.9) corresponds approximately to the inverse ratio of their thermal conductivities (0.37).

Especially if brass plates are used, heating can benefit significantly from a pressure increase, but in addition to the heating time also the temperature dependent stress strain behavior of the contact plate material must be considered when choosing the surface pressure. According to [21], the flow stress of brass alloys similar to the one used here is in the range of 25 MPa - 50 MPa only at a temperature of 550°C, which is only 50 K higher than the contact plate temperature considered here. This means that even though the curves in Fig. 6 suggest that an increase in pressure beyond 15 MPa can still bring a slight reduction of the heating time in case of heating plates made of brass, this advantage must be carefully assessed against the risk of plastic deformation of the contact plates.

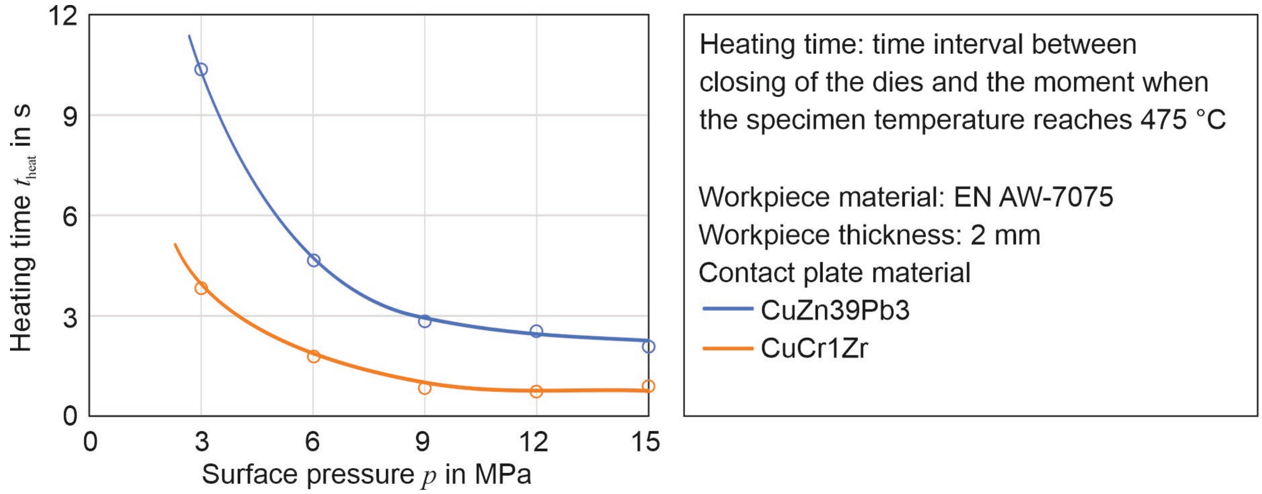

Fig. 6. Heating times for different contact plate materials as function of the surface pressure.

Fig. 7 compares the maximum heating rates $\dot{T}$ of the different contact plate materials for a plate thickness of 2 mm as a function of surface pressure. The heating rates were determined in each case in the range of the linear temperature increase with the maximum slope (see Fig. 4). In addition, the heating rate of the conventionally used contact plate material 1.4828 from [17] was plotted in the diagram for comparison. It can be clearly demonstrated that the maximum heating rates for contact plates made of copper and brass, respectively, are similar at 3 MPa surface pressure. Above 6 MPa surface pressure, however, the values measured for the copper plates increase significantly above the heating rates determined for the brass plates. The maximum heating rates are reached at 12 MPa, but the values for 9 MPa and 15 MPa are at a comparable level. The maximum values amount to approximately 1690 K/s in case of heating plates made of copper and 370 K/s in case of heating plates made of brass. Thus, the maximum heating rate achieved using brass plates is only 23 % of the heating rate achieved using copper plates. At first glance, these results are contrary to those in Figure 6, where the largest difference between the contact plate materials is at 3 MPa and the smallest at 15 MPa. However, the maximum heating rate $\dot{T}$ evaluated here only describes the linear range of the heating process, whereas the heating time t_{heat} covers heating up to 475°C. Heating up to 475°C takes considerably more time and involves strongly non-linear parts of the heating curve (see Fig. 4).

Finally, the heating rate of steel 1.4828 from [17] was plotted. The test conditions were slightly different but still comparable. Especially, the contact plate temperature was slightly lower (480°C instead of 500°C) and the considered workpiece material was a different aluminum alloy with slightly lower heat capacitance but featuring the same thermal conductivity. Moreover, the heating plates and the workpiece were larger in [17], but it can be assumed that this has no significant influence of the heating behavior so the heating rate can be compared. Fig. 7 shows that at a surface pressure of 4.5 MPa, the steel reaches lower heating rates than the predicted heating rates for both materials investigated here. This proves the high potential of the investigated materials in particular the copper alloy for contact heating of aluminum workpieces compared to conventionally used materials as e.g. 1.4828.

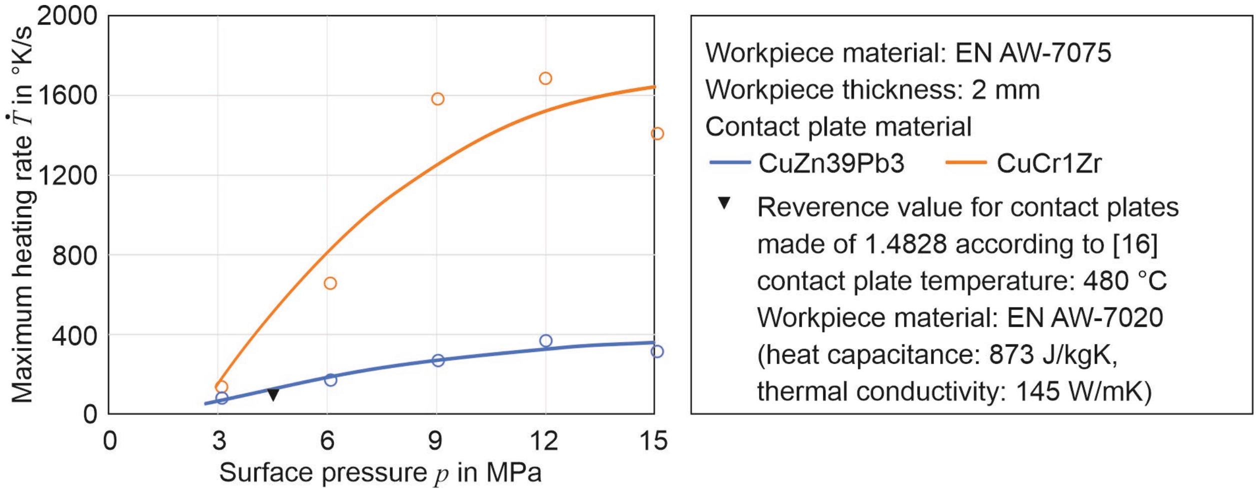

Fig. 7. Maximum heating rates for different contact plate materials as function of the surface pressure.

Summary

In the present study, the effects of two different contact plate materials (copper and brass alloys), five surface pressures and five plate thicknesses on the heating time of the aluminum alloy EN AW-7075 up to the solution heat treatment temperature of 475°C were investigated. A specially manufactured contact heating tool with comprehensive temperature and force measurement was used for this purpose. It was observed for all specimens that fast heating can be realized. Especially at a surface pressure of 9.0 MPa or more, the heating times could be minimized. A further increase in surface pressure is not recommended, because the benefit in terms of further reduction of the heating time is marginal and the strength of the contact plate materials at elevated temperatures relevant for this heating process is limited.

Furthermore, as expected, the heating time decreases significantly with a reduction in sheet thickness. For sheet thicknesses of 1.0 mm and 2.0 mm, heating times of less than 1.0 s could be achieved when heating with the copper plates. The minimum value at 1.0 mm sheet thickness was 0.2 s. The maximum heating rate of 1690 K/s could be achieved at a surface pressure of 12 MPa. This shows the high potential of contact heating especially when heating components with rather small sheet thicknesses. For the highest sheet thicknesses tested here (5.2 mm) and consequently also for the highest volume of the specimen, still a heating rate of 165 K/s could be achieved at the lowest surface pressure. This is significantly more compared to more conventional heating technologies such as furnace heating.

Finally, a comparison of sample heating with brass contact plates was performed. It was found that compared to the heating plates made of copper, especially at low surface pressure significantly higher heating times were necessary, but an increase in surface pressure still allowed reducing the heating time to 2.0 s. Altogether, the following key results were obtained:

- Surface pressures in the range of 9.0 MPa - 12 MPa are recommended for contact heating of aluminum workpieces. Higher pressure brings no further positive effects.
- The lower the sheet thickness, the more positive the contact heating concept. Maximum heating rates of 1690 K/s could be achieved using copper plates.
- Contact heating using copper plates is significantly faster compared to brass plates and the conventionally used steel plates. Heating via brass plates, however, benefits more from an increase in surface pressure.

The presented results prove that contact heating can be realized within the press if suitable surface pressure is applied.

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