Characterization of Heat Transfer Coefficient of Lightweight Alloys in Kirksite Dies

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Abstract. The heat transfer coefficient (HTC) is an important parameter in the finite element (FE) modelling of warm and hot forming operations. The HTC, among other parameters, governs the FE model predictions for the cooling rate within the blank and the resulting constitutive behaviour and formability. In the current work, the HTC of two aluminum alloys (AA5182-O and AA7075-T6) and one magnesium alloy (ZEK100) is characterized. Blanks were heated in a convection furnace and subsequently quenched in a set of kirksite dies under various contact pressures. Kirksite is a zinc-based alloy commonly used in prototype tooling. The temperature-time (T-t) profile of the blanks and die were measured during each quenching experiment. The resulting T-t profiles were input into a Matlab script, which calculated the HTC using an iterative regression technique.

1. Introduction
As warm and hot metal forming operations become more common, the understanding of the heat transfer between the blank and tooling has also become crucial. The heat transfer coefficient (HTC) between the surfaces of the blank and tooling governs, among other parameters, the rate of cooling that the blank will experience while it is formed. The cooling rate can be an important consideration in the warm forming (WF) and hot forming (HF) operations, such as the HF of 7000-series aluminium alloys [1,2] and the WF of AA5182 [3].

The HTC for a given alloy can vary significantly depending on the quenching medium and interface conditions. For example, when quenched in steel dies, the HTC of AA7075 ranges from 350 to 2800 W/m²-K [4]. The HTC of several aluminium and magnesium alloys between a pair of steel die has been characterized by Omer et al. [4] and other investigators [5,6].

Typically, dies used in a forming operation are made of steel alloys. However, for prototypes, tools are often made of kirksite, a zinc-based alloy. There remains a need, therefore, to characterize the HTC for the same alloys between a set of kirksite dies. Such data is important since differences in cooling rate between prototype kirksite and production steel dies need to be accounted for since constitutive behaviour and formability are strong functions of temperature. In the current work, the HTC is characterized as a function of die contact pressure, for AA5182-O, AA7075-T6 and ZEK100 sheet metal blanks in contact with a set of kirksite dies.

2. Experiments
The experimental methodology in this work largely followed that used by Omer et al. [4]. Blanks made of AA5182-O (1.5 mm thick), AA7075-T6 (2.0 mm thick) and ZEK100 (1.6 mm thick) were quenched...
between a pair of flat dies made of kirksite. The flat dies are shown in Fig. 1. The blanks were 125 x 125 mm in size, and contained a 19 mm cut-out at the centre, as shown in Fig. 2. A k-type thermocouple was placed into the cut-out of the blank using thermal tape, as shown in Fig. 2. Experiments were performed with and without tape (using an adhesive) and no measurable difference was found in the HTC. The tape was chosen over the adhesive because tape was easier to place.

This thermocouple placement ensured that the thermocouple did not make contact with the die surfaces, and therefore, only measured the temperature of the blank. The surface of the die was also instrumented with a type-k thermocouple 9.5 mm away from the blank, which is shown in Fig. 1. Both the blank and die thermocouples were connected to an Omega OMB-DAQ-55, which recorded temperature at a frequency of 5 Hz.

The experimental procedure consisted of heating the blanks to 300°C in a convection furnace. Once the blanks reached 300°C, they were manually transferred into the die set which was then closed and held at different contact pressures to simulate the heat transfer conditions during warm forming. The transfer process from furnace to die set took 6s and the blank spent an additional 2s resting on the die surface before the dies were closed. All three alloys were held under contact pressures of 5, 10 and 20 MPa. For each contact pressure, three repeats were conducted for each material.

Fig. 1. (a) The pair of flat dies, made of kirksite, used for the HTC experiments, (b) the placement of the blank onto the die and the thermocouple that measured the temperature of the die surface, and (c) a schematic of the flat die and blank geometries.
Fig. 2. Blank geometry (dimensions in millimetres) and the thermocouple placement on the edge of the blank.

3. Calculating HTC

Calculating the HTC, from the temperature-time curves obtained from experiments, consisted of three steps: filtering, correcting the die temperature, and calculating HTC. In the first step, filtering, a 5-point moving average filter was applied to the temperature-time curves for the die and blank.

The second step, which is the die temperature correction, was conducted because the thermocouple that measured the die surface temperature was not in the direct contact zone between the blank and die. The die temperature in the direct contact zone was calculated using

\[ T_{\text{die}} = T_{\text{experimental}} + C_{p\text{blank}} \frac{m_{\text{blank}}}{A_{\text{blank}}} \left( \frac{T_{\text{blank}}^{n+1} - T_{\text{blank}}^n}{\Delta t} \right) \left( \frac{\Delta x^2}{k} \right) \]

where \( T_{\text{experimental}} \) is the die temperature recorded during experiments, \( C_{p\text{blank}} \) is the specific heat capacity of the blank, \( m_{\text{blank}} \) is the mass of the blank, \( A_{\text{blank}} \) is the cross-sectional area of the blank in contact with the dies, \( T_{\text{blank}} \) is the blank temperature, \( k \) is the thermal conductivity of the kirksite dies, the superscript \( n \) represents time step, \( \Delta t \) is the difference in time between two consecutive temperature measurements and \( \Delta x \) is a discretization interval. A derivation of the above equation, which is available in Omer et al. [4], involved using a central difference approximation using finite differences. Table 1 shows the inputs used for the above equation.

Table 1. Thermal properties used for the blanks and die in the HTC calculation procedure. \( T \) refers to temperature in Celsius.

| Property                     | Value                        |
|------------------------------|------------------------------|
| Thermal conductivity of dies | 114 W/m-K                    |
| AA5182-O – specific heat capacity | 897 + 0.452T [7]               |
| AA7075-T6 – specific heat capacity | 960 + 0.2T [8]               |
| ZEK100 – specific heat capacity | 1020 [9]                     |
The final step, calculating the HTC, was done using a summation over the temperature-time curves:

\[
h = \frac{\sum \left[ \ln \left( \frac{T - T_{\text{die}}}{T - T_0} \right) C_p^{\text{blank}} \frac{m^{\text{blank}}}{A^{\text{blank}}} \times t \right]}{\sum t^2}
\]

Omer et al. [10] derived the above equation using the steady state equation for thermal conduction and by using a least squares regression to isolate for the HTC, \( h \).

4. Results

Fig. 3 shows temperature-time profiles obtained for some of the scenarios tested. The calculated HTC values for all three materials are shown in Table 2, along with the standard deviations in the measurements. Fig. 4 plots HTC (between kirksite and steel dies) as a function of contact pressure for all three alloys. HTC is shown to increase with contact pressure for each alloy.

![Fig. 3](image-url)

**Fig. 3.** (a) Temperature-time profiles obtained from quenching experiments between kirksite dies for some test scenarios. (b) Also shown are the temperature-time curves from Omer et al. [4] for the same scenarios using steel dies.
Table 2. Calculated values for HTC in kirksite dies and standard deviations. For comparison, the HTC values obtained by Omer et al. [4] for steel dies are also shown.

| Material & Contact Pressure | HTC for kirksite dies (W/m²-K) | HTC for steel dies (W/m²-K) |
|-----------------------------|---------------------------------|-----------------------------|
| AA5182 – O (5 MPa)          | 1200 ± 65                       | 672 ± 9                     |
| AA5182 – O (10 MPa)         | 1892 ± 94                       | 961 ± 15                    |
| AA5182 – O (20 MPa)         | 2008 ± 102                      | 1235 ± 22                   |
| AA7075 – T6 (5 MPa)         | 842 ± 35                        | 501 ± 8                     |
| AA7075 – T6 (10 MPa)        | 1088 ± 38                       | 620 ± 10                    |
| AA7075 – T6 (20 MPa)        | 1455 ± 44                       | 750 ± 8                     |
| ZEK100 (5 MPa)              | 768 ± 48                        | 500 ± 4                     |
| ZEK100 (10 MPa)             | 956 ± 55                        | 667 ± 7                     |
| ZEK100 (20 MPa)             | 1145 ± 80                       | 749 ± 15                    |

Fig. 4. HTC as a function of contact pressure. The data points represent the average of three repeats and the error bars represent standard deviation in the calculated HTC values.

Table 2 and Fig. 3 also compare the measure HTC from the current experiments using kirksite dies and results from Omer et al. [4] for the same alloys using steel dies. In general, the HTC for the kirksite dies was higher than for steel dies. Overall, ZEK100 and AA7075-T6 experienced similar HTC values in the kirksite dies, which is consistent with the HTC values that Omer et al. [4] obtained for steel dies. AA5182-O experienced higher HTC values than ZEK100 and AA7075-T6.

5. Discussion and Conclusions

The HTC values between kirksite dies were found to be significantly higher than those of steel dies for the same blank material under similar contact conditions. Both aluminum alloys, though having very different values for HTC, experienced a similar percentage increase in HTC from kirksite to steel. ZEK100, on the other hand, experienced a smaller increase.

Quantitatively, AA5182-O experienced an increase of 38-49% in its HTC between kirksite and steel dies; AA7075-T6 experienced an increase of 40-48% and ZEK100 experienced an increase of 30-35%. It can be said, therefore, that the cooling rate experienced by blanks made of the three alloys considered in this work is going to be higher in kirksite dies than in steel dies, if contact pressure and other forming conditions are the same. This point is supported by the temperature-time curves in Fig. 3, which show that at the same contact pressure (5 MPa in the figure), the quenched blanks experienced higher cooling rates in kirksite than they did in steel. This trend is true for all three alloys characterized in this work.
Fig. 3 shows that at higher contact pressures, the blanks experienced a higher cooling rate, which would indicate that they have a higher HTC. The increase in HTC with respect to contact pressure is also consistent with other sources in the literature [4,11,12]. The HTC values obtained in this work, which are shown in Table 2 and Fig. 4, can be used to model a warm or hot forming finite element operation that consists of a tool set made of kirksite.

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