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Technical Paper

Warm forming die design, Part II: Parting surface temperature response characterization of a novel thermal finite element modeling code

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ABSTRACT

The majority of the research activities in the area of warm forming are concentrated on demonstrating or simulating the improved formability associated with forming lightweight materials such as aluminum alloys at elevated temperatures. However, the ability to design the proper thermal management system within the forming tool is a critical aspect to delivering this technology as a viable, stable production alternative to traditional stamping. This work begins to address the thermal stability issues of this process by examining the impact of process cycle time on the parting surface temperature response. Cycle times of 10, 15, 30, and 300 s were evaluated using a reciprocating surface and a self-heated experimental block of 1020 steel fitted with resistance cartridge heaters. The presented results indicate that cycle time does not significantly impact the steady-state temperature response at the parting surface for a well-insulated die that has proper thermal management. Parting surface experimental results were compared to values obtained numerically and through the use of the novel thermal finite element analysis software PASSAGE/Forming®.

1. Introduction

Warm forming often refers to the enhanced sheet metal formability of aluminum alloys in the temperature range of 150–350 °C in a matched die set. However, warm forming research has historically only dealt with the enhanced tensile/LDR/LDH formability, material characterization, simulation, and modeling parameters primarily in the laboratory environment. There has been little emphasis for the transfer of this research to the production level which is evident by the lack of commentary by Toros et al. [1] in a recent comprehensive review of the technology. A critical area of concern when transferring this technology to production rates is thermal stability, i.e. the ability to maintain the temperature throughout the die and at the forming surface. Lack of thermal stability can result in a variable temperature gradient within the die causing die distortion and reduced forming capability. Therefore, the manufacturing objective then becomes to design for thermal stability with the understanding that stability within the die transfers to stability at the die surfaces.

Researchers have attempted to characterize surface temperatures for various applications using several different experimental techniques and mathematical models. Tercelj [2] embedded thermocouples just beneath the surface and used extrapolation through finite difference method to gage the surface temperature during hot metal forming. Osman [3] used a spring-loaded thermocouple pressed against a surface to read surface temperature. However, the spring-loaded approach underestimated temperature by as much as 30% (with respect to degrees Celsius) in comparison to surface-mounted thermocouple results and required a correction factor based on the inverse method to accurately determine the surface temperature. An inverse approach is commonly used when attempting to determine the surface temperature for many researchers; i.e. determining the outer wall temperature of an object by knowing the inner wall/fluid temperature. Lin [4] used the inverse method to characterize surface thermal behavior of a heated cylinder. Chen [5] and Ling [6] also used the inverse method for estimating the surface temperature for various heat conduction problems.

This work has utilized the implicit thermal finite element software called PASSAGE/Forming® (PASSAGE) for model formulation and computation of surface temperatures. PASSAGE is a steady-state analysis tool that is discussed in its entirety by Harrison et al. [7] and can perform temperature optimization on the parting surface using the error minimization technique from the target temperature. Characterizing the response of the die parting surface for the forming of lightweight materials, such as aluminum, has

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Table 1
Material properties for experimental block.

Block parameters	
Material	Steel 1020
Dimensions (mm)	300 × 200 × 120
Density (kg/m^3)	7870
Specific heat (J/kg K)	520
Thermal conductivity (W/m K)	51.9
Blanket insulation	
Thickness (in)	1
Density (kg/m^3)	96
Thermal conductivity (W/m K)	0.06 @ 473.15 K

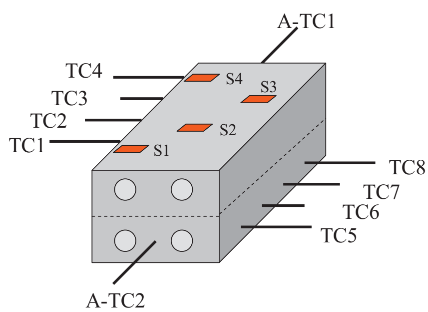

Fig. 1. Schematic of the experimental block with surface thermocouples.

been accomplished using an experimental block of 1020 steel fitted with resistance cartridge heaters and a reciprocating surface. The reciprocating or moving surface simulates the action of a forming press on a laboratory scale. Temperature measurements were made using surface thermocouples to determine the thermal response of the surface for various cycle times while embedded thermocouples capture the temperature within the die. Experimental results have been compared to predicted values by PASSAGE for cycle times of 10, 15, 30, and 300 s. The results of this correlation showed that cycling produces only a small variation in the temperature at the parting surface and has little effect on the ability for the die to regain or maintain a steady-state temperature throughout the process for a thermally stable die. The second phase of this warm forming die design development work is intended to validate the surface temperature assumptions of this design and modeling tool that will subsequently support the delivery of thermally stable die systems for high-volume warm forming production of lightweight materials.

2. Experimental approach

Previous work has characterized the internal temperature reponse of a steel block through the use of embedded thermocouples to validate the thermal stability of insulated surfaces [7]. Results indicated that PASSAGE could successfully predict the internal temperature response of the steel block within an accuracy of 3% with respect to the target temperature. A similar experimental approach has been used for the evaluation of forming cycle on the predictive capability of PASSAGE at the parting surface for a simple die geometry.

2.1. Steel block description

A block of 1020 steel with the dimensions and material properties listed in Table 1 was machined to house four 300 mm cartridge heaters rated at 1500 W and 208 V; a schematic of the block is shown in Fig. 1. The block was set to a target temperature of 473 K (200 °C). Two active, process regulating (control) K-type[1] thermocouples (TC), labeled A-TC1 and A-TC2, were embedded in the center of each zone and communicated to the PID[2] controller the current temperature of the block in relation to the set temperature. Eight K-type monitoring thermocouples were positioned 12 mm from the top and bottom of the block surfaces at varying depths. Surface thermocouples were positioned just above the upper embedded monitoring thermocouple locations using Kapton tape. The surface thermocouples, labeled S1 through S4, and monitoring thermocouples, labeled TC1 through TC8, were connected to a data acquisition system that recorded temperature at a specified sampling rate. Temperature was measured in units of Celsius and converted to Kelvin.

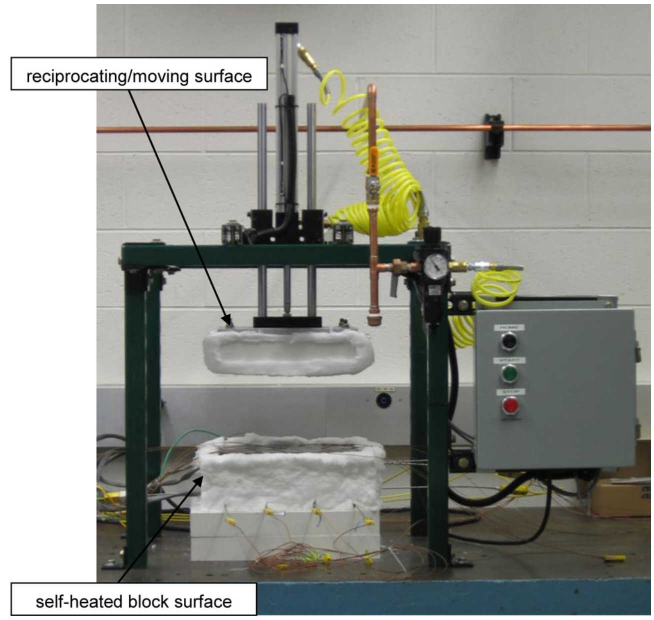

Fig. 2. Experimental set-up for reciprocating surface.

2.2. Reciprocating surface description

The experimental set-up shown in Fig. 2 was designed to simulate the opening and closing of a die, as in conventional stamping process, with minimal heat loss at the parting surface. This configuration is intended to represent an isothermal process in which a warm blank is in contact with a warm die; thus assuming minimal heat transfer difference between surfaces. The parting surface is the portion of the die in contact with the sheet. The moving insulated surface was comprised of 1 inch blanket insulation and 2 inches of board insulation. The insulated surface was mounted to a linear actuator with a travel height of approximately 330 mm and pressure of 60 psi. The time required to fully cycle the actuator took approximately 4.0 s. Various cycle times were evaluated as shown in Table 2 that varied the hold time at the top of the stroke, thus varying the open time, while the closed time remained fixed at 6 s. A Micrologix 1000 PLC was used to control the number of cycles. Temperature data was collected in 1-s intervals for the following test duration time: 10-min steady-state, 20-min cycling, and 10-min steady-state. The initial 10-min interval was used to determine the initial steady-state temperature response. The final 10-min

[1] A K-type thermocouple is the most common general purpose thermocouple which is inexpensive and has an active range of −200 °C to +1350 °C.
[2] Proportional-integral-derivative (PID) controller is a generic closed feedback loop mechanism commonly used in industrial control systems.