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Temperature analysis during the drawing of an aluminum cylindrical cup

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Abstract. Both the plastic deformation and the friction forces generate heat in sheet metal forming processes. This yields a temperature rise on the blank and tools, which is mainly dictated by the blank properties and the press speed. Although modest values of temperature rise yield negligible changes in the mechanical behavior of metals, the lubricant properties are rather influenced by the temperature. Thus, the deep drawing of an aluminum cylindrical cup was selected to evaluate, experimentally and numerically, the temperature variation of the forming tools and blank at room temperature. Different values of punch speed are compared to evaluate the impact of the heat losses to the environment. The experimental results show that the temperature rise on the die surface is higher than 9ºC when the punch speed is 10 mm/s. The temperature is underestimated by the finite element model due to the isothermal conditions imposed on the forming tools.

1. Introduction

In sheet metal forming at room temperature, the heat generated by plastic deformation and friction leads to the increase of the blank temperature. This is particularly relevant in mass production lines since the repeated processing of material results in a periodic input of heat into the tools. Moreover, high contact pressures contribute to the plastic deformation of the asperities of the blank surface, increasing the effective contact area with the tools, i.e. heat transfer coefficient increases [1]. This temperature increase depends on the forming rate, the blank's mechanical behavior, and the tools-blank contact conditions. Temperature variations in the forming process can have a high impact on the material forming behavior, lubrication conditions and wear performance, contributing to variability [2]. Thus, in order to improve the sheet metal forming robustness, the heat generated by plastic deformation and friction should be quantified. The thermo-mechanical analysis, through finite element modeling, can help to improve knowledge concerning the influence of the temperature variation in the forming conditions.

This study analyses the temperature variation when forming an aluminum alloy at room temperature, which is complemented by thermo-mechanical finite element analysis aiming to understand the impact of the punch speed on the temperatures experimentally measured. Additionally, the contribution of the plastic deformation and friction to the generated heat is also analyzed. Isolated thermal conditions are simulated to assess the heat generated, as well as the heat conduction through the blank. Finally, convection was then applied to replicate experimental results.

2. Cylindrical cup forming

The deep drawing of an aluminum cylindrical cup at room temperature was selected to evaluate, experimentally and numerically, the temperature variation of the forming tools and blank [3]. Different values of punch speed are compared to evaluate the impact of the heat losses to the environment on the cup temperature.

2.1. Experimental setup

The experimental apparatus used to perform the cylindrical cup forming is presented in Figure 1 (a), while the geometry of the tools is presented in Figure 1 (b). In addition to the forming force, the temperature is monitored using five thermocouples, placed in different locations (blank, die, punch and blank-holder), as shown in Figure 1 (b). The circular blank (60 mm diameter) is trimmed from sheets of AA6016-T4 aluminum alloy (1.05 mm thickness), which is lubricated to reduce the friction forces.
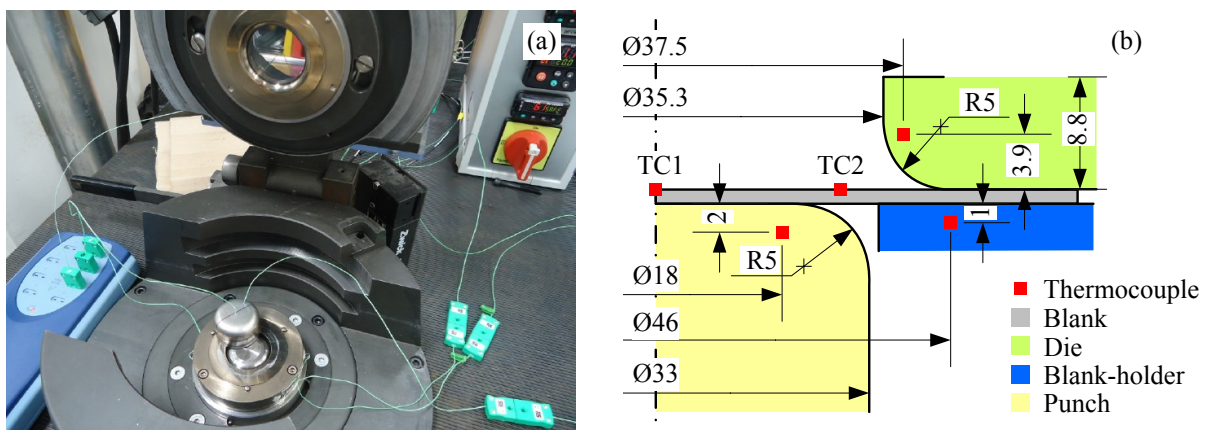

Figure 1. Setup of the cylindrical cup forming: (a) experimental apparatus; (b) scheme of the tools geometry, including the location of the thermocouples (all dimensions are in mm).

Figure 2 presents the stress–strain curve of the alloy under analysis, considering three different values of crosshead velocity in the uniaxial tensile test, highlighting that this material is not strain rate sensitive at room temperature. This behavior is replicated in the punch force evolution during the deep drawing operation, which is presented in Figure 3 for two different values of punch velocity. The increase of the punch force after 22 mm of punch displacement is related to the ironing of the blank between the die and the punch [3].
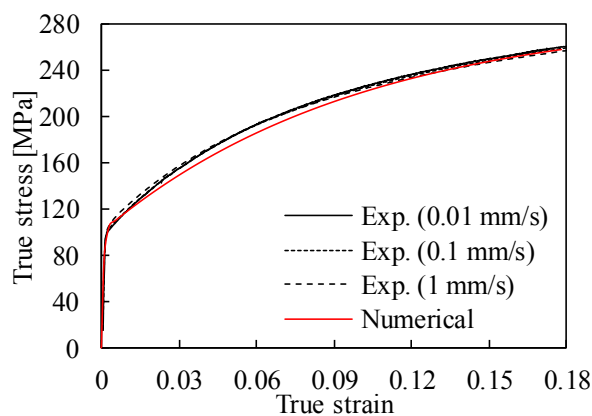

Figure 2. Comparison between experimental and numerical uniaxial tensile stress–strain curves for three different values of crosshead velocity.
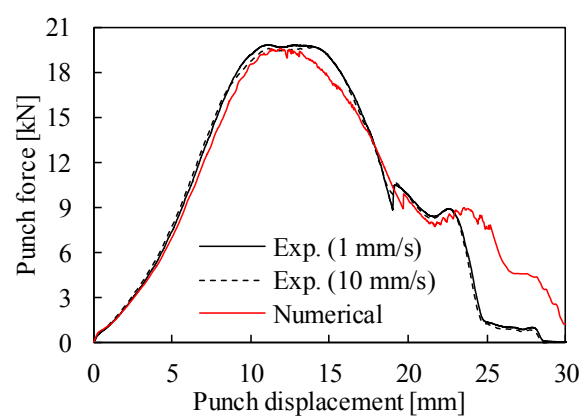
Figure 3. Comparison between experimental (two distinct values of punch velocity) and predicted punch force evolution.

2.2. Finite element model

The thermo-mechanical analysis was performed with the in-house finite element code DD3IMP [4,5], assuming that the forming tools are rigid and isothermal. The plastic behavior of the aluminum alloy is described by the isotropic work hardening (Voce law) and the anisotropic yield criterion (Barlat'91). Both are assumed as temperature independent for the range under analysis. The parameters of the constitutive model were obtained from [6]. The thermal properties of this aluminum alloy are: thermal capacity c_p=850 J/(KgK) and thermal conductivity k=184 W/(mK) [7]. The friction coefficient (μ=0.15) was evaluated by fitting the predicted punch force evolution to the experimental data (see Figure 3). Only one-quarter model is simulated, allowing to perform the discretization of the blank with 5910 hexahedral finite elements (2 layers through the thickness). Full integration is adopted in the thermal problem while selective reduced integration is adopted in the mechanical one.

3. Results and discussion

Assuming isolated thermal conditions for the blank, the evolution of the temperature variation evaluated in four different nodes (aligned with the rolling direction) is presented in Figure 4, for two values of punch velocity. The nodes are initially located in the blank center (Node1) and at 15 mm (Node2), 20 mm (Node3) and 25 mm (Node4) from the center. The temperature increases due to the heat generated both by plastic deformation and by the friction forces. Since the forming time is 10 times larger using the lower punch velocity, the thermal conduction leads to a temperature homogeneity after forming (Figure 4 (a)).
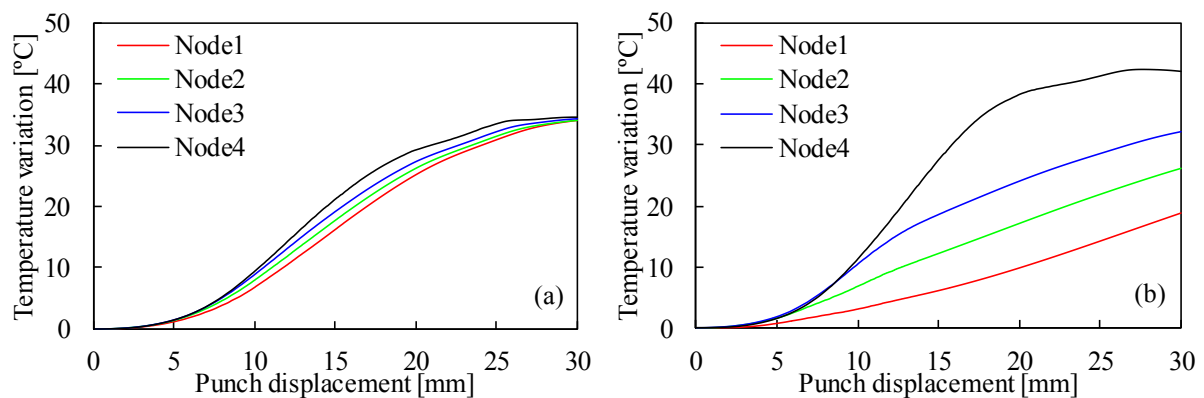

Figure 4. Evolution of the temperature variation in four nodes of the blank, assuming isolated thermal conditions, predicted for two values of punch velocity: (a) 1 mm/s; (b) 10 mm/s.
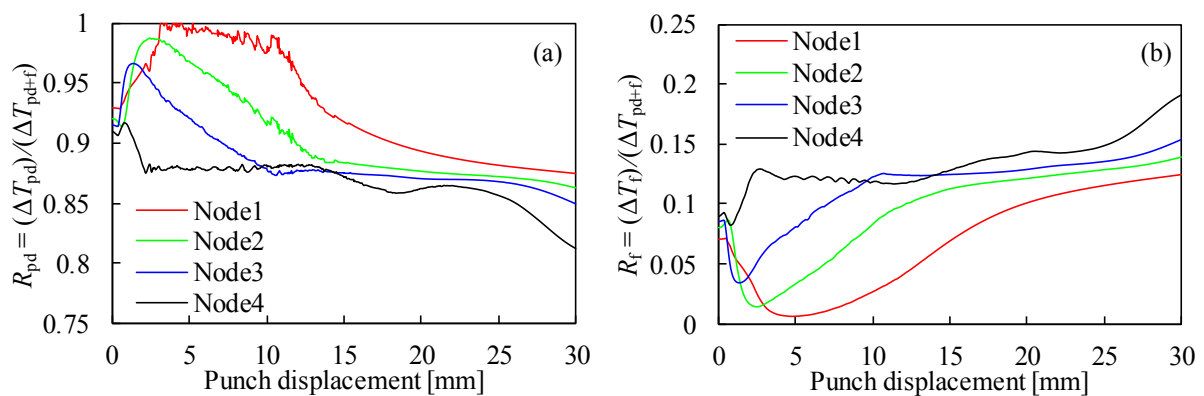

Figure 5. Predicted heat generated during the cup forming assuming isolated thermal conditions and 10 mm/s of punch velocity: (a) ratio of heat generated by plastic deformation; (b) ratio of heat generated by friction forces. Temperature variation considering the heat generated by: plastic deformation (ΔT_{pd}); by friction (ΔT_f); and by both (ΔT_{pd+f}).

In order to quantify the ratio of heat generated by plastic deformation and by friction forces over the total, the temperature variation is evaluated under different conditions, i.e. considering only the heat generated by plastic deformation and considering only the frictional heating. Since the action of the thermal conduction is lower for large values of punch velocity, the temperature ratio is calculated considering 10 mm/s of punch velocity and isolated thermal conditions (Figure 5). Globally, 90% of the heat generated comes from plastic deformation and the remaining 10% derives from the friction forces.

Figure 6 presents the temperature variation along the initial radial coordinate of the blank, at the end of the forming process, considering isolated thermal conditions and free convection to air (h=10 W/m^{2}K) [8]. The heat loss to the environment occurs through the upper and lower surfaces of the blank, while the air is assumed at room temperature (initial blank temperature). The influence of the free convection on the predicted temperature variation is higher for the lower punch velocity (1 mm/s) due to the largest operation time (30 seconds). Indeed, the effect of the free convection becomes negligible for the punch speed 10 times higher, as highlighted in Figure 6. Besides, the thermal conduction within the blank is less effective, which leads to a thermal gradient between the cup bottom and the rim of about 30ºC (see Figure 6 (b)). Since most of the heat is generated by plastic deformation (Figure 5), which occurs predominantly on the flange and die radius [5], the temperature is always higher close to the cup rim.
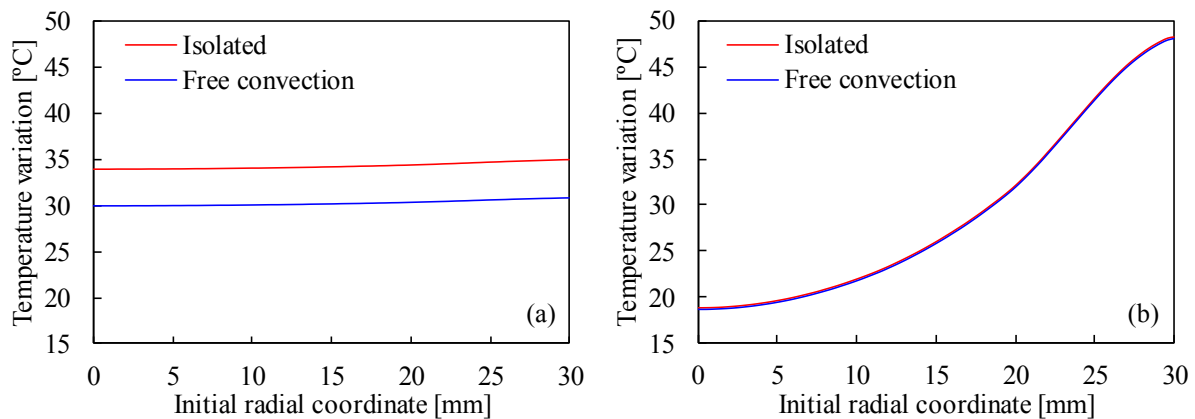

Figure 6. Temperature variation of the blank after forming, comparing isolated thermal conditions with free convection (h=10 W/m^{2}K), predicted for two values of punch velocity: (a) 1 mm/s; (b) 10 mm/s.
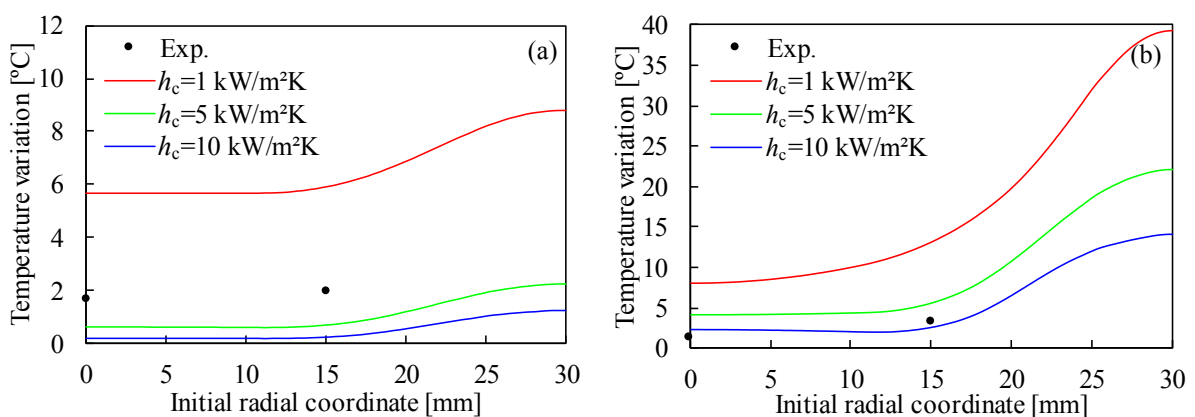

Figure 7. Temperature variation of the blank at 20 mm of punch displacement, comparing different values of thermal contact conductance, predicted for two values of punch velocity: (a) 1 mm/s; (b) 10 mm/s.

In order to account the heat loss to the tools, the thermal contact conductance is considered using the model proposed in [9], where the interfacial heat transfer coefficient is dependent on the gap value.

Since this coefficient depends on several factors (temperature, contact pressure, surface roughness, material properties), three different values are adopted in the present study. The temperature variation along the radial direction of the blank, predicted for 20 mm of punch displacement, is presented in Figure 7 for two values of punch velocity. The predicted temperature rise is strongly reduced by considering the heat loss to the tools, particularly for 1 mm/s of punch displacement. Indeed, the temperature is approximately constant in the cup bottom, increasing along the cup wall, as shown in Figure 7.
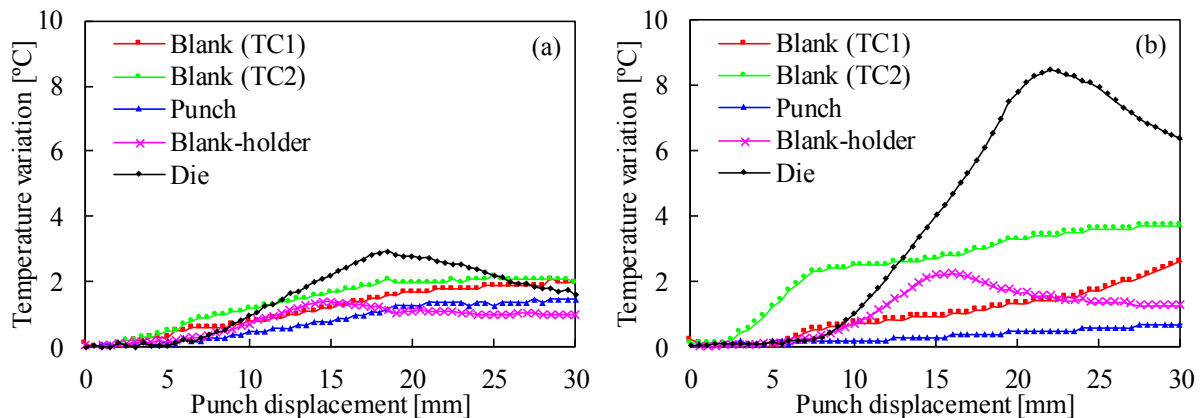

Figure 8. Experimental temperature variation, evaluated both in the blank and in the tools (punch, blank-holder and die), considering two values of punch velocity: (a) 1 mm/s; (b) 10 mm/s.
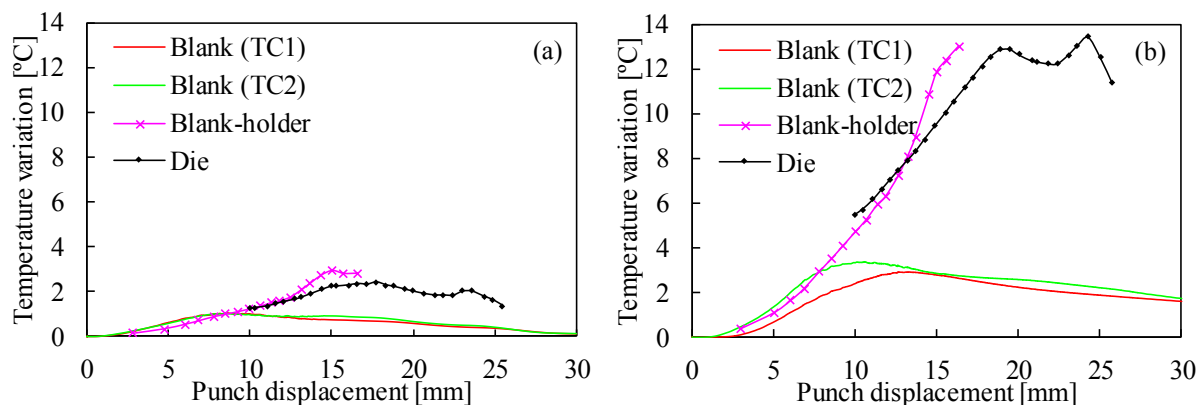

Figure 9. Numerical temperature variation evaluated in different regions of the blank, considering two values of punch velocity: (a) 1 mm/s (h_c=5 kW/m^{2}K); (b) 10 mm/s (h_c=10 kW/m^{2}K).

Figure 8 presents the experimental evolution of the temperature variation on the blank and tools (see Figure 1 (b)), obtained for two values of punch velocity. Globally, the temperature is higher for 10 mm/s of punch velocity because the heat losses by both natural convection and contact conductance are lower (3 seconds of forming time). On the other hand, since most of the plastic deformation of the blank occurs on the flange and die radius [5], the maximum value of temperature arises in the die, as shown in Figure 8, in agreement with [10]. Note that the same comment is valid for the sliding friction forces. Regarding the temperature on the blank, the minimum arises in the center of the cup bottom (TC1), due to the location of the heat sources (away from the blank center).

The numerical prediction of the temperature evolution is presented in Figure 9, considering the interfacial heat transfer coefficient h_c=5 kW/m^{2}K and h_c=10 kW/m^{2}K for 1 mm/s and 10 mm/s of punch velocity, respectively. These values were selected taking into account the comparison between numerical and experimental temperatures shown in Figure 7. Since the numerical model assumes isothermal conditions for the tools (room temperature), the temperature of the tools is evaluated by selecting the node of the blank closest to the corresponding thermocouple location. The die and blank-

holder present the highest temperature values due to the contact with the cup wall, which is warmer than the cup bottom (Figure 7). The decrease of the blank temperature (cup bottom) after 15 mm of punch displacement is a consequence of assuming the tools at room temperature, which is not observed in the experimental measurements. Hence, the accuracy of the numerical model can be improved by accounting the thermal conduction within the tools.

4. Conclusions

This study presents the temperature analysis of tools and blank during the deep drawing of an aluminum cylindrical cup, under room temperature conditions. The heat generated by plastic deformation and friction forces is considered in the finite element model, as well as the heat loss to the environment (air) by natural convection and the heat loss to the tools by contact conductance. The numerical results are compared with experimental measurements of the temperature evolution (blank and tools). The numerical results show that 90% of the heat generated comes from plastic deformation and the remaining 10% derives from the friction forces. On the other hand, since the punch velocity defines the forming operation time and, consequently, the amount of heat energy loss, two punch velocities are evaluated. Increasing the punch speed leads to a global increase of the temperature on the blank and tools. Indeed, experimental results show that the temperature rise on the die surface is higher than 9ºC when the punch speed is 10 mm/s. On the other hand, the accuracy of the numerical model can be improved since the tools are assumed isothermal.

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