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Experimental and numerical studies on the warm deep drawing of an Al–Mg alloy

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ABSTRACT

The warm deep drawing of circular AA5754-O aluminium alloy blanks was investigated both experimentally using specially designed equipment and numerically using a fully coupled thermo-mechanical finite element model. Cylindrical cups were prepared with a heated die and blank-holder. The split-ring test was used to measure the effects of the temperature on the springback process from room temperature to 200 °C. Temperatures above 150 °C were found to greatly affect the force/displacement response during the forming process and the ironing phase, the earing profile and the springback effect. Tensile and shear tests were also performed to study the temperature-dependent mechanical responses.

To simulate this process, a temperature-dependent anisotropic model for the material was implemented in the commercial code ABAQUS/Standard, based on the UMAT interface for user-material models. The parameters of a phenomenological Hockett–Sherby hardening model and a power law strain rate dependency were identified using data obtained in uniaxial tensile and shear tests at various temperatures and strain rates, in order to account for both the temperature and the viscous effects in the coupled thermomechanical constitutive law. Von Mises isotropic criterion and Hill'48 anisotropic yield criterion were also adopted to describe the material mechanical behaviour. The influence of the contact with friction conditions in the forming process (i.e. punch force evolution, thickness distribution along the cup wall and earing profiles) was also analysed. The numerical results obtained with the calibrated parameters generally showed a good match with the experimental temperatures. The results highlighted the importance of the correct choice of the yield criteria. The Hill48 criterion showed difficulties in the correct prediction of the springback process for this aluminium alloy.

1. Introduction

Nowadays, aluminium alloys are increasingly used in the automotive industry, since they allow weight reduction in body-in-white. However, aluminium alloys are known for being more prone to springback phenomenon than conventional steels. In order to overcome such problems, good results on the stamping process are obtained for aluminium alloys when the temperature is elevated to an intermediate temperature, below the recrystallisation temperature. This process is called warm forming. The warm press forming of aluminium alloy sheets promoted a great interest and during the last few years, especially with the 5xxx series (Al–Mg alloys), the warm forming process has become a widely used alternative to the classical forming processes performed at room temperature.

Ayres [1] investigated first the potential of warm forming by deep drawing a circular cup and observed that the cup height increased with increasing forming temperature and/or decreasing punch speed for an AA5182-O alloy. As also illustrated by Abedrabbo et al. [2], this new forming process is particularly suitable for use with aluminium alloy sheets since their formability and ductility are enhanced by the warm temperatures. Bolt et al. [3] reported that the formability of typical automotive Al–Mg sheet alloys, such as AA5754-O, can be greatly improved by using warm forming methods at temperatures ranging from 100 to 250 °C.

However, at room temperature, 5xxx series alloys suffer from the problem of Dynamic Strain Ageing (DSA) which is at the origin of the resulting stretch marks affecting the surface quality of the parts. In fact, DSA is known to cause the Portevin–Le Châtelier (PLC) effect and the corresponding Lüder's line surface defects. Microscopically, the PLC effect is due to the interaction of foreign

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atoms with dislocations which is characterised, on the macroscopic scale, by plastic instabilities, i.e. repeated load drops due to rapid localised plastic strain during the overall deformation. As a non-linear dynamic mechanism phenomenon, the aging rate and the waiting time of mobile dislocation at the obstacles affect the nucleation and propagation of PLC bands. However, as mentioned in our previous studies [4,5], the PLC effect can be prevented in tension and shear tests by deforming the sheet metal above a critical temperature in a specific range of strain rates. Al–Mg sheet alloys are in fact strain rate dependent, and show negative Strain Rate Sensitivity (SRS) (which is another indication of DSA) in specific temperature and strain rate ranges. Kabirian et al. [6] have reported that although the flow stress decreases with increasing strain rates during quasi-static loading below the critical temperature, the response recorded at higher temperatures shows positive strain rate sensitivity in the same strain rate range. It is therefore of great importance to improve our knowledge of the thermo-mechanical behaviour of Al–Mg alloys in order to determine the optimum forming temperature and speed.

Another advantage of warm aluminium alloy forming processes is that high temperatures affect the stress state in the parts obtained and thus decrease the springback effects. The large springback process which occurs after aluminium alloy sheets have been formed at room temperature is one of the main reasons why this material has not been more widely used in the automotive industry. However, since very few studies were performed, apart from [7,8] which focused on the springback effects occurring in aluminium alloys under warm forming conditions, very little is known about the mechanisms underlying the springback behaviour of these materials at high temperatures. Kim and Koç [9] investigated numerically the effects of temperature gradients between the tools on the springback in the case of a simple 2D channel drawing process. They also analysed the dependence of springback processes on the blank holder force, friction conditions and forming rate, but no comparisons were made with experimental results obtained at high temperatures. In most attempts to predict the springback effects at high temperatures, some questions have consistently arisen about the accuracy of the numerical models used and the most suitable combination of modelling variables to adopt for this purpose.

The aim of this paper is to present the results of experimental springback tests performed on an AA5754-O alloy under warm forming conditions, and to compare them with the predictions obtained in numerical simulations. In our previous studies [8,10], the warm forming of this material was studied under isothermal conditions after applying a uniform temperature increase. In the present study, a new experimental setup designed for performing the deep drawing of a cylindrical cup by heating the tools separately was used. Naka and Yoshida [11] performed cylindrical deep drawing tests on an AA5083-O alloy at various punch temperatures and Li and Ghosh [12] performed biaxial warm forming tests on a heated rectangular die-punch device. Both works reported that the formability increased when selective localised heating strategies were applied to the forming tools, causing an inhomogeneous distribution of the temperature in the blank. Therefore, the aim was to confirm this improvement of the formability and to study the effects of warm forming conditions on the springback process. For this purpose, the springback was determined by measuring the opening of a ring sampled from the sidewall of a newly formed cylindrical cup. This test, which is called the split-ring test, was first presented by Demeri et al. [13]. It provides a simple and effective mean of predicting the forming and springback performances of alloys based on experimental measurements.

Contrary to our previous studies [8,10], due to the dimensions of the die and punch chosen, an ironing phase at the end of the forming operation occurred with this new experimental setup. This ironing phase was due to an increase of the blank thickness and the fact that the gap between the punch and the die was not sufficiently large to allow the blank material to flow. The ironing process typically imposed high contact forces, normal to the surface of the punch and the die, which can lead to the occurrence of galling, particularly for aluminium alloys. The influence of the temperature on this ironing phase was also studied in this paper.

It was also proposed here to investigate the relevance of the finite element analysis (FEA) approach to predicting the forming process, the ironing phase and the springback of an aluminium alloy under warm forming conditions, focusing in particular on the following two numerical parameters: the yield criterion and the friction coefficient. These two parameters have been found to considerably affect the results of numerical simulations, as established in our previous studies [14,15]. Numerical analyses were therefore performed using the fully coupled thermo-mechanical finite element model (FEM) version of ABAQUS [16]. The modified Hockett–Sherby hardening law with temperature and strain rate functions presented here was used to describe the thermo-elasto-viscoplastic behaviour of the material. This constitutive model was implemented in ABAQUS via a user-defined material subroutine (UMAT). The numerical parameters required were based on experimental data. In particular, blank temperatures recorded during the process were used to estimate the conductivity coefficients involved in the heat transfer between the tools and the blank. The effects of the temperature and the relationships between local temperatures and the properties of the material were also simulated. All these simulations were performed with a set of numerical parameters in order to mainly investigate the effects of the temperature on the springback predictions.

2. Warm forming laboratory tools

The material used in this study was sampled from a rolled sheet of 1-mm gauge AA5754-O aluminium alloy (Al–3%Mg), which is often used in the automotive industry to obtain inner body panels. The material was initially in the ‘O’ condition, which means that it was fully annealed. Since recrystallisation usually occurs in Al alloys of this kind only at temperatures above 350 °C (beyond this temperature, no recovery is possible), the blanks were always heated in this study to temperatures below 250 °C.

Cylindrical cup forming tests (Swift tests) were carried out on a Zwick/Roell Amsler BUP 200 sheet metal testing machine. A diagram of the deep-drawing procedure is presented in Fig. 1(a). This machine was adapted for performing these tests under warm forming conditions at the laboratory scale (see Fig. 1(b)). The blanks were machined using the original cutting tool with which the BUP 200 machine was equipped. The experimental equipment was composed of a set of forming tools made of hardened XC38CrMoV5 steel. All the surfaces of the tools were finely ground in order to reduce the friction. The blanks could be heated along with the die and the blank-holder (BH) in the 100–200 °C temperature range.

The geometry of the tools is given in Fig. 2. The tools were all axisymmetric, with a inner die diameter of 35.25 mm and an outer punch radius of $d = \phi_P = 33$ mm. The shoulder radius of both the die and the punch was 5 mm. The circular aluminium blank had a diameter of $D = 60$ mm. The drawing ratio of this cylindrical cup forming process was $\beta = D/d = 1.8$. The BH force at the beginning of the deep drawing operation was set at 6 kN, and this force was exerted until the cup reached a height of 21 mm with a constant punch travel speed of 1 mm/s. To fully draw the cup, a punch displacement of 32.5 mm was imposed (see Fig. 1(a)). An oil lubricant (Jelt Oil) was applied manually to both sides of the