International Journal of Machine Tools & Manufacture 48 (2008) 1535–1545

Contents lists available at ScienceDirect

International Journal of Machine Tools & Manufacture

journal homepage: www.elsevier.com/locate/ijmactool

The design of a formability test in warm conditions for an AZ31 magnesium alloy avoiding friction and strain rate effects

G. Palumbo *, D. Sorgente, L. Tricarico

Department of Mechanical and Management Engineering, Polytechnic of Bari, Viale Japigia 182, Bari, Italy

ARTICLE INFO

Article history:
Received 18 January 2008
Received in revised form
18 June 2008
Accepted 20 June 2008
Available online 28 June 2008

Keywords:
AZ31 magnesium alloy
Forming limit curve
Constant strain rate
Finite element analysis

ABSTRACT

In this study, a test procedure is proposed to investigate the formability of the AZ31 Mg alloy in warm conditions (below 200 °C) while keeping the equivalent strain rate constant. Both the variables (temperature and strain rate) play a key role on the plastic behaviour of Mg alloy sheets. A numerical–experimental approach was adopted with the aim of designing equipment and test procedures, which can perform formability tests in warm conditions. Since finite element simulations need reliable and accurate data to model the forming process, the authors propose a methodology to evaluate the forming limit curve (FLC) according to both the temperature level and the (equivalent) strain rate value. Using the designed equipment and proposed approach, it is possible to: (i) force material failure in the central part of the specimen; (ii) define a constant temperature in the failure region; (iii) determine a constant equivalent strain rate in the failure region. Experimental tests in the present paper were carried out using a digital image correlation system, which is able to acquire strain maps during the entire forming process; experimental data allowed for both a validation of numerical results and the acquisition of important information about the effects of strain rate and temperature on the FLC of the AZ31 Mg alloy.

1. Introduction

Nowadays a number of sectors such as the aerospace and automotive industries, electronics and sport require the production of lightweight parts. Above all in the automotive field, the adoption of materials with a favourable strength/weight ratio (such as aluminium, magnesium or titanium alloys) can increase the fuel efficiency of automotive transportation; in particular, Mg alloys show an advantageous strength/weight ratio (density: 1740 kg/m^3; UTS: 160–360 MPa), high thermal conductivity and good damping and electromagnetic shielding properties [1,2]. However, it is often quite expensive and complex to replace steel in the structure or body of vehicles with Mg or Al alloy, principally because such alloys exhibit poor formability at room temperature, much lower than typical steel sheets. Nevertheless, a great deal of research in literature, also by the authors, confirms the effectiveness of the temperature and strain rate in improving the ductility of both Mg and Al alloys [3–8]; in addition, if a small grain size microstructure is obtained, further formability improvements can be expected due to an easier non-basal slip system activity [9].

It is important to highlight that the parameter strain rate, being strictly related to the pile up of dislocations and the recrystallisation phenomena, is as important as the parameter temperature when considering the plastic behaviour in warm conditions; if increased, it determines a reduction of both material softening and post-uniform elongation, while increasing the flow stress [3,4,10,11]; the investigations of previous authors on the deep drawing process [12,13] revealed the potential to drastically improve the limit drawing ratio of such alloys (up to 3.4 for Mg and up to 2.9 for Al) by adopting the local heating/cooling system and the appropriate punch speed.

Thus, it is necessary to take into account the temperature as well as the strain rate when investigating the formability of Mg and Al alloys; it is well known that the above-mentioned material property (formability) is generally measured by the evaluation of the forming limit curve (FLC), obtained by connecting points that indicate the maximum strain that the material can experience in a plane stress state in both the principal directions (major and minor strains) [10,11,14–16]. Indeed, the major advantage of this tool is that FLC can also easily be used as a fracture criterion in the finite element (FE) simulations of sheet-metal-forming applications [11,17,18]. However, no unique standard test currently exists to evaluate FLC; ISO standards simply provide generic guidelines about test conditions and procedures [19]. Research at both industrial and academic level has attempted to define shared guidelines for the determination of FLCs [20]. Yet the lack of a

* Corresponding author.
E-mail addresses: g.palumbo@poliba.it (G. Palumbo), d.sorgente@poliba.it (D. Sorgente), tricarico@poliba.it (L. Tricarico).

0890-6955/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijmachtools.2008.06.010

commonly accepted technical solution is even more evident when formability is investigated at temperatures other than room. In this case, the most common applications are the stretch-forming tests of specimens with various widths using a hemispherical punch (Nakajima test) where all the equipment is heated by an external furnace or by cartridge heaters [11,14,15]. The Marciniak test, based on a similar concept but using a flat end punch and driving sheet in order to avoid fractures over the punch radius, is seldom adopted [10]. Further formability tests can be found in literature, performed by means of a pneumatic bulge apparatus [16] with elliptic dies at different geometries (only on the right side of the FLC), or by means of specific apparatus for cruciform specimens [21,22]. Tensile tests on specimens with appropriate widths may also be adopted to evaluate FLC (only on the left side) [23], but no applications exist at elevated temperatures. In any case, most of the above-mentioned FLC data do not take the strain rate into account; indeed, it is often not considered at all [14,15,17] or its effect on FLCs is only qualitatively evaluated by means of tests at a constant punch speed but not at a constant strain rate [10,11]. Only Siegert [16] highlights that the pneumatic bulge test is performed at a constant strain rate using an appropriate pressure profile, but the FLC is limited to the right side.

In order to increase the accuracy of numerical simulations and to adopt appropriate and reliable material data, one possible solution is the calculation of critical strain pairs using one of the numerous strain localisation models available in literature [24]. In this way, evaluating the material properties at different temperatures and strain rate levels by standard tests, appropriate FLCs can be calculated for every type of working condition [25–27]. The drawback of such an approach is that a model cannot reliably predict the FLC of every type of material; even for the same material, the same model may not be adequate at every temperature or strain rate condition.

2. Aim of the present study

The main objective of the present study is to evaluate a test procedure to investigate formability in warm conditions while keeping the equivalent strain rate constant. As a case study, an AZ31 Mg alloy was investigated. The research involved both numerical simulations and experimental tests.

In order to perform experimental tests and measure the FLC according to the above-mentioned fundamental process parameters (temperature and strain rate), specific stretch-forming equipment was designed and created, embedding a heating system and a digital image correlation (DIC) for the strain measurement. The design of the equipment is described in Section 3.

An evaluation of the test procedure was performed by analysing the heating and the forming phase of the test, both described in Section 4. The FE approach was used in order to evaluate: (i) the optimal shape of the punch; (ii) the test conditions able to force specimen failure in the central region; and (iii) the punch speed profile able to keep a constant equivalent strain rate in the region of the specimen where failure occurred.

Finally, in Section 5, the experimental activity aimed at both validating the test procedure and investigating AZ31 formability is described.

The principal expected advantages of the test procedures proposed by the authors include the possibility of: (i) assembling the equipment on a standard tensile single-action test machine; (ii) measuring the FLC of the material at a fixed value of the temperature as well as the strain rate; and (iii) avoiding any friction effect on the acquisition of critical major and minor strain.

The FLCs evaluated using the proposed methodology can thus be implemented in FE models more reliably than with other formability data in literature, which do not contain information about temperature and strain rate effect or which simply take into account the tool speed instead of the strain rate.

An additional aim of this study was to obtain a greater understanding of AZ31 Mg alloy formability by performing tests, which changed both the temperature level (100–200 °C at $2\times10^{-3}\,s^{-1}$) and the strain rate (2×10^{-3}–$2\times10^{-4}\,s^{-1}$ at 100 °C).

3. Design of the experimental equipment

The equipment for evaluating formability in warm conditions was designed in order to provide a uniform and constant temperature distribution on the specimen. It was obtained by means of an electric heating system embedded in the punch, which reached the maximum temperature level in the centre of the specimen and forced a fracture in this region. An FE analysis was performed in order to determine the optimal shape of the punch: 3D models (code: ABAQUS/Standard) were used to simulate the heating phase and the temperature distributions determined by both the hemispherical-shaped punch (usually adopted for the Nakajima test) and the flat punch.

The model consisted of a draw die, a blank holder and a 92 mm diameter punch. The convective heat flux was modelled assuming a sink temperature equal to 27 °C; the thermal radiation was also taken into account. Thermal properties [28,29] and model characteristics adopted in the simulations are shown in detail in Table 1.

The temperature maps in Fig. 1 show the specimen with a width–length ratio (WLR) equal to 0.5, tested with thermal power equal to 600 W. These maps confirmed that the hemispherical punch could not determine a uniform temperature distribution on the specimen because of the small contact region between the punch and the specimen at the very beginning of the test.

In addition, in the case of a flat punch (Fig. 2), the temperature distributions along both the longitudinal direction (nodes from 1 to 46) and the transversal direction (nodes from 1 to 24) show that in the central region of the specimen, the temperature can be

Table 1
Parameters adopted in the FE model

Parameter	Tool steel	AZ31
Density (kg/mm^3)	7.85×10^{-6}	1.74×10^{-6}
Specific heat (J/kg K)	460	1025
Thermal conductivity (W/mm K)	0.017	0.159
Thermal expansion coefficient	11×10^{-6}	27.2×10^{-6}
Convection with ambient (W/mm^2 K)	100	
Sink temperature (°C)	27	
Emissivity	0.5	–

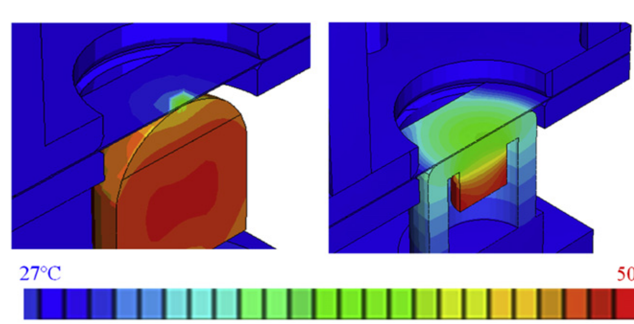

Fig. 1. Temperature distributions on the specimen obtained by a flat end punch and by a hemispherical punch.