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SUPERPLASTIC SHEET METAL FORMING WITH FOCUS ON THE WARM BULGE TEST AND ITS IN-PROCESS MONITORING

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ABSTRACT: Material characterisation is of prime importance in understanding its response to forming loads, which in turn influence the product design. The flow stress in plastic loading defines the evolution of the yield surface and depends on a variety of factors such as strain, strain rate and temperature. The degree of influence of the strain rate increases at higher temperatures. This effect can be well described with superplastic forming, in which the material is loaded very slowly at superplastic temperatures. This paper deals with monitoring of process parameters during superplastic sheet metal forming of magnesium alloys, with special emphasis on in-process measurements for bulge test purposes at elevated temperatures. The strain evolution near the part's pole region has been recorded in-process by using the ViALUX photogrammetric strain analysis system AutoGrid. The recorded data provides a lot of information about the forming process such as evolution of strains, strain rate, flow stress and the limit strains, which allows determining all relevant material and process parameters for superplastic forming.

KEYWORDS: Superplastic, Bulge Test, In-Process Monitoring, Magnesium Alloys

1 INTRODUCTION

Superplastic sheet metal forming processes enable the production of otherwise difficult-to-manufacture or non-manufacturable complex part geometries due to their unique properties; which would apart from that require a large number of manufacturing stages or only can be manufactured as an assembly of joined components in conventional manufacturing. Low tool costs, high design complexity coupled with low forming speeds that lead to long process times make this forming process an interesting alternative especially for small lot sizes. [1, 2] - “Currently more than 40 ‘in-production’ aircrafts and twenty different automobiles are using superplastically formed aluminum components”. [3]

Superplasticity describes capability of certain fine-grained polycrystalline materials to undergo extensive tensile plastic deformation under specific temperature and load conditions prior to failure. Hexagonal close packed (hcp) structured magnesium (Mg) alloys show poor formability at room temperature as also at moderately elevated temperatures, which makes superplastic forming of such alloys fairly attractive. The knowledge of the superplastic material and process characteristics is very important for designing a superplastic forming process. For that very reason the testing procedure should be as similar as possible to the forming technique (in this case the cavity/female forming). The pneumatic bulge test satisfies this condition and is therefore chosen to determine the material and process characteristics [4, 5, 6]. This paper focuses upon investigations on the characterisation of material and forming properties for superplastic sheet metal forming with a pneumatic bulge test and its in-process monitoring.

2 PNEUMATIC WARM BULGE TEST

2.1 EXPERIMENTAL SETUP

The functionalities and a schematic of the pneumatic warm bulge test setup used in this investigation are shown in Figure 1. An undeformed sheet metal is clamped between the die on the lower side and the blank holder on the upper side. The clamping force is chosen sufficiently high in order to prevent material flow into the forming zone. Gas pressure acts on the upper side of the sheet, thereby forcing the sheet metal to expand into the die cavity. The tool is heated and the sheet is interposed unheated, for which reason a certain time period should be allowed between clamping and pressurising in order to achieve stable working conditions. The die is modular in design. The circular die used in this work has a die opening diameter of 100 mm and a edge radius of 5 mm. The modular design allows the use of elliptical die openings to generate different states of stress.

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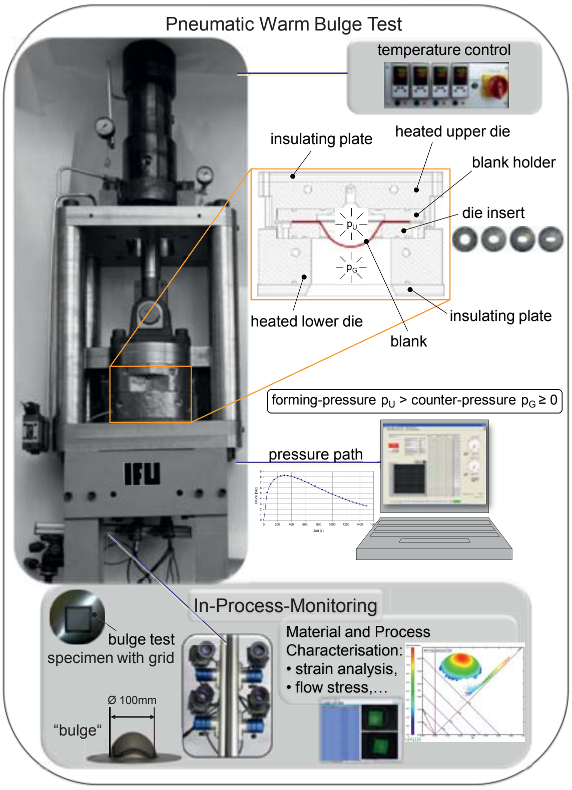

***Figure 1:** Setup - Pneumatic Warm Bulge Test*

Integrated ViALUX photogrammetric strain measurement system AutoGrid permits in-process recording of the superplastic forming process. For that reason the bulge test specimens have to be prepared with a contrasting grid before bulging. At first a black paint was applied on the blank surface. Then a grid was marked on the lower surface of the bulge test specimen by using a solid-state laser.

2.2 MATERIAL CHARACTERISATION

As mentioned earlier, the superplastic forming process is very sensitive to process conditions: knowledge of accurate material properties appears crucial. Due to this there are many publications about material characterisation for superplastic forming purposes. The warm bulge test provides a suitable method for material characterisation with regard to the cavity forming process without the need to resort to the uniaxial tensile test required. Concerning this matter, a few papers worth mentioning referring especially to the pole height or constant forming pressure are [6, 7, 8, 9]. The presented pneumatic warm bulge test provides through its in-process monitoring the development of strains ε and curvature ρ in the area of the bulge pole during the forming process. With this information all relevant material properties can be calculated:

- strain rate $\dot{\varepsilon}_3$ $(=\dot{\varepsilon}_{\max})$
- flow stress k_f
- strain-hardening exponent n
- strain-rate sensitivity index m
- material constant C

The strain rate $\dot{\varepsilon}_3$ directly results from the development of strains on the bulged surface. At equi-biaxial state of stress, either Tresca or Von Mises yield criterion could be used for calculating the flow stress with Equation (1) under the assumption of uniform thinning:

$$k_f = p \cdot \left(\frac{\rho + s}{2 \cdot s} \right) \tag{1}$$

To calculate the flow stress by developing the commonly used membrane theory; the, instantaneous pressure p, instantaneous bulge curvature ρ and instantaneous sheet thickness s at the bulge pole are needed. [10, 11, 12]

Generally, the mechanical behaviour of superplastic materials at constant temperatures is described by an enhancement of the approximation according to Ludwik [1, 7, 13]:

$$k_f = C \cdot \varepsilon^n \cdot \dot{\varepsilon}^m \tag{2}$$

The strain-hardening exponent n is defined as the gradient of the flow curve (flow stress k_f over thickness strain ε_3) in the double logarithmic coordinate system and can be expressed by the following equation:

$$n = \frac{\partial \ln(k_f)}{\partial \ln(\varepsilon)} \tag{3}$$

The gradient of the flow curve (flow stress k_f over thickness strain rate $\dot{\varepsilon}_3$) in the double logarithmic coordinate system corresponds to the strain-rate sensitivity index m:

$$m = \frac{\partial \ln(k_f)}{\partial \ln(\dot{\varepsilon})} \tag{4}$$

The material constant C can further be calculated from the experimental stress-strain curve by using the calculated strain-hardening exponent n, and strain-rate sensitivity index m values in Equation (2).

3 EXPERIMENTS

3.1 DETERMINATION OF FLOW LIMIT DIAGRAMS

As already presented in [14] flow limit diagrams for AZ31 and ZE10 (initial sheet thickness 1.6 mm, forming temperature 400°C) were determined by using the pneumatic warm bulge test with circular and elliptical dies (Figure 1). The forming pressure was based on the following analytical pressure profile developed by Banabic [1] to maintain a satisfactorily constant strain rate:

$$p = 2 \cdot \frac{1 + \alpha \cdot \left(\frac{b_0}{a_0} \right)^2}{\sqrt{1 - \alpha + \alpha^2}} \cdot \frac{s_0}{b_0} \left(e^{\frac{2-\alpha}{2 \cdot \sqrt{1-\alpha+\alpha^2}} \cdot \dot{\varepsilon} \cdot t} - 1 \right)^{\frac{1}{2}} \tag{5}$$

$$\cdot e^{\frac{-3}{2 \cdot \sqrt{1-\alpha+\alpha^2}} \cdot \dot{\varepsilon} \cdot t} \cdot C \cdot \dot{\varepsilon}^m$$

where a_0 is the semi-major axis and b_0 the semi-minor axis of the die opening (in case of a circular die $a_0 = b_0$). The initial sheet thickness is s_0 and t the time. The symbol α is defined as:

$$\alpha = \frac{1}{2} \cdot \left(1 + e^{1 - \frac{a_0}{b_0}} \right) \tag{6}$$

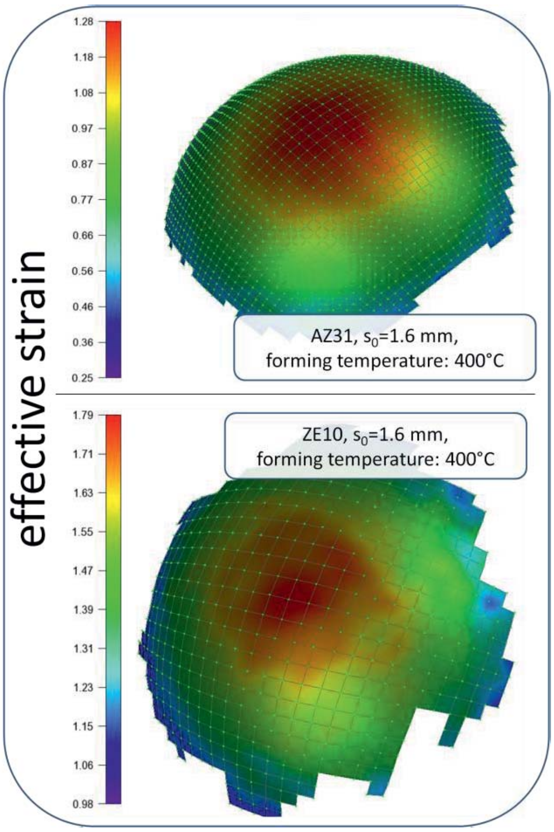

Figure 2: *Effective strain distribution of AZ31 and ZE10*

Figure 2 shows that higher maximum strains could be achieved with ZE10 (maximum effective strain ε_{eff} = 1.79) as compared to AZ31 (maximum effective strain ε_{eff} = 1.28). The in-process monitoring was necessary because specimens consisting out of ZE10 often burst explosively. Such specimens could not be measured afterwards. Therefore the last image set before fracture was analysed.

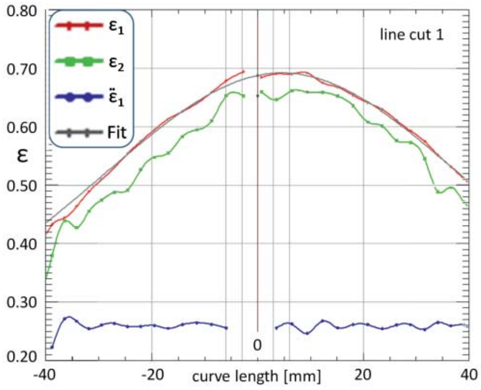

Figure 3*: AZ31 bulge test – line cut (ISO 12004)*

A determination according to ISO 12004 is also supported by the strain analysis system AutoGrid. Figure 3 shows the results for pneumatic warm bulging of AZ31 (s_0=1.6 mm, 400°C, 'optimised' pressure path) one image set before fracture (using a circular die insert). As depicted in this case, no necking and non-predominant anisotropy could be analysed.

3.2 FURTHER MATERIAL CHARACTERISATION USING AZ31 MATERIAL

The initial sheet thickness of the AZ31 sheets was 1.6 mm and the pressure path was calculated by Equation (5). Required material and process parameters to use Equation (5) were determined also by the pneumatic bulge test. For this reason the following results come from one already 'optimised' bulge test (maximum effective strain ε_{eff} = 1.4 compared to ε_{eff} = 1.28 in Figure 2) concerning strain rate and its 300 evaluated image sets. This test was repeated at least twice to ensure repeatability. The first image set starts 200s after pressurising the blank (0.5 frames / second).

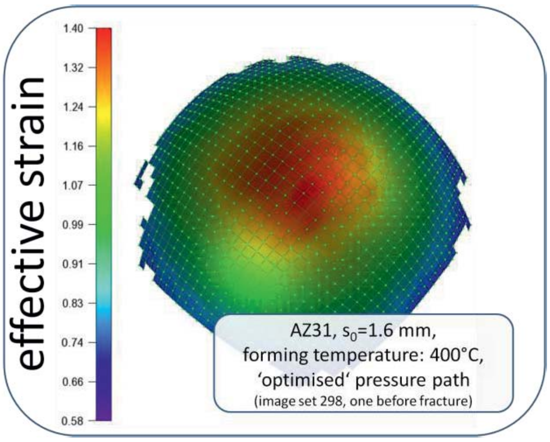

Figure 4: *Strain distribution of 'optimised' bulge test*

Figure 5 shows the influence of strain on the flow stress. In an interval of almost constant strain rate the flow stress remains constant, consequently the strain-hardening exponent within this interval is very small (n ≈ 0) and can be neglected.

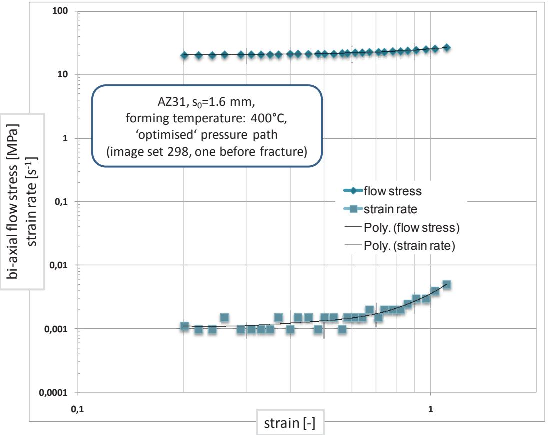

Figure 5: *Influence of strain (ε_3) on the flow stress and corresponding strain rate*

The strain sensitivity index *m* could also be determined since, the strain rate increases at the end of the forming process. So there are different strain rates with corresponding different flow stresses (Figure 6). But in this case the strain sensitivity index *m* would be calculated under neglect of an influence of strain-hardening exponent *n*. Determination of strain-rate sensitivity index *m* in consideration of the strain-hardening exponent *n* is possible by determining bi-axial flow stresses for different strain rates at equal strain.

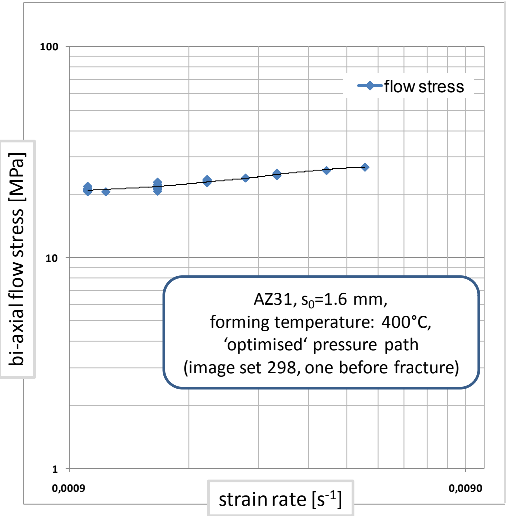

***Figure 6:** Influence of strain rate on the flow stress*

4 CONCLUSIONS

A pneumatic warm bulge test and its possibilities due to in-process monitoring were presented. The theoretical determination of all relevant material and process parameters like flow stress, strain rate, strain-rate sensitivity index *m* and strain-hardening exponent *n* were showed using AZ31 material. Furthermore it was shown that the in-process monitoring contributes towards better understanding of the forming process and supports the optimisation of the pneumatic warm bulge test. Flow limit curves (at fracture) for the relevant state of stress could be also determined as showed before. Experiments comparing the magnesium alloy ZE10 to AZ31 showed that ZE10 reaches higher strain values before fracture than AZ31 material.

ACKNOWLEDGEMENT

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REFERENCES

[1] Vulcan M.: Der pneumatische Tiefungsversuch und seine Anwendung in der superplastischen Aluminium-Blechumformung. Oberusel: DGM Informationsgesellschaft Verlag, 2006.

[2] Liewald M., Kappes J., Pop R.: Superplastic Forming of Magnesium Alloys. In: 65th Annual World Magnesium Conference, pages 115-121, 2008.

[3] Barnes A. J.: Superplastic forming 40 years and still growing. Journal of Materials Engineering and Performance 4, pages 440-454, 2007.

[4] Abu-Farha F. K., Shuaib N. A., Khraisheh M. K., Weinmann K. J.: Limiting strains of sheet metals obtained by pneumatic stretching at elevated temperatures. CIRP Annals – Manufacturing Technology 57, pages 275-278, 2008.

[5] El-Morsy A., Akkus N., Manabe K., Nishimura H.: Evaluation of superplastic characteristics of tubular materials by multi-tube bulge test. Materials Letters 60, pages 559-564, 2006.

[6] Giuliano G., Franchitti S.: The determination of material parameters from superplastic free-bulging tests at constant pressure. International Journal Machine Tools & Manufacture 48, pages 1519-1522, 2008.

[7] Aoura Y., Ollivier D., Ambari A., Del Santo P.: Determination of material parameters for 7475 Al alloy from bulge forming tests at constant stress. Journal of Materials Processing Technology 145, pages 352-359, 2004.

[8] Giuliano G.: Thickness and strain rate at the sheet dome apex in superplastic bulge forming tests. In: 12th International Esaform Conference on Material forming, 2009.

[9] Franchitti S., Giuliano G., Palumbo G., Sorgente D., Tricarico L.: On the optimisation of superplastic free forming test of an AZ31 magnesium alloy sheet. In: 11th International Esaform Conference on Material forming, 2008.

[10] Doege E., Behrens B.-A.: Handbuch Umformtechnik. Springer-Verlag Berlin Heidelberg, 2007.

[11] Hecht J.: Werkstoffcharakterisierung und Prozessauslegung für die wirkmedienbasierte Doppelblech-Umformung von Magnesiumlegierungen. Meisenbach Verlag Bamberg, 2007.

[12] Kaya S., Altan T., Groche P., Klöpsch C.: Determination of the flow stress of magnesium AZ31-O sheet at elevated temperatures using the hydraulic bulge test. International Journal of Machine Tools & Manufacturing 48, pages 550-557, 2008.

[13] Elsenheimer D., Groche P.: Determination of material properties for hot hydroforming. Production Engineering – Research and Development 3, pages 165-174, 2009.

[14] Liewald M., Kappes J.: In-Prozess-Messung beim pneumatischen Warmtiefungsversuch. Springer-VDI-Verlag: wt Werkstattstechnik online 99 Nr. 10, pages 753-760, 2009.