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An Investigation, Using Standard Experimental Techniques, to Determine FLCs at Elevated Temperature for Aluminium Alloys

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Abstract: An experimental procedure has been developed for the determination of FLCs at elevated temperatures. The GOM ARGUS system was employed for measuring surface strain based on pre-applied grids (pattern), and limit strains were determined according to the ISO 12004-2:2008 standard. Forming limit curves (FLCs) have been determined for AA5754 under warm forming conditions in an isothermal environment. The tests were carried out at various temperatures up to 300^{o}C and forming speeds ranging from 5 – 300 mm s^{-1}. Results reveal the significant effect of both temperature and forming speed on FLCs of AA5754. Formability increases with increasing temperature above 200^{o}C. Formability also increases with decreasing speed. The presented FLC results show that the best formability exists at low forming speed and the high temperature end of the warm forming range.

Keywords: Aluminium alloys; AA5754; Elevated temperature; Formability; Forming limit curves; Warm forming

1 Introduction

Forming Limit Curves (FLCs) are used in sheet metal forming for determining the likely occurrence of failure, for given strain conditions. They represent the limit strains for different strain paths in the principal strain space and are widely used for formability simulation in metal forming process. Many publications are concerned with the determination of FLCs both experimentally and theoretically, and various testing methods are used to obtain experimental FLCs. Two of the most commonly used test methods are the Marciniak type test [1-3] and Nakajima type test [3-6]. Different geometries and widths of test-piece have been used by different researchers, when using these tests, to produce different strain states, from uniaxial to plane strain, to equibiaxial tension. Normally the test-pieces have either a parallel waisted section [6] or strips [7] or hourglass-shaped geometry [4-5, 8], except the equibiaxial test-pieces. In addition to the above mechanical stretching tests, a recent method called pneumatic stretching test in which gas is used for forming, has been successfully employed to determine a high temperature FLC for magnesium alloy [9]. The pneumatic stretching tests can be used to determine only the right quadrant of an FLC, i.e, no data for negative minor strain can be obtained.

Determination of limit strains often requires applying patterns to the sheet metal surface and determining strain through the deformed patterns. Determination of the FLCs in a laboratory environment is described in ISO 12004-2:2008 standards. In-situ, online monitoring systems using digital image correlation (DIC) technique have been widely accepted as currently the most accurate and repeatable method for determining FLCs at room temperature. However, difficulty arises with systems which lack a viewing "window" and accessibility to the work-piece during testing, such as when a furnace is required in order to achieve elevated temperatures.

Aluminium alloy components are an important contribution to light-weight vehicles for improving energy efficiency. However, formability of aluminium alloys at room temperature often hinders their further application in the automobile industry. Interest has thus arisen in warm forming technology and improved formability has been reported [10-16]. For warm forming, elevated temperature FLCs are very important for traditional feasibility simulations. They also provide a means of calibrating/validating material models, such as the one being developed at Imperial College London [17], which in principle is able to predict stress-strain state for any combination of temperature and strain rate. Some effort has been made to determine FLCs of aluminium alloys at elevated temperature [1-4, 10, 18-19]. However, the reported FLC data are sparse, and the methods used to determine them were different from one another and more information obtained from test methods which are recognised as sound are necessary to provide a base of data in which confidence can be placed.

The objective of the present work is to determine FLCs for AA5754 under warm forming conditions at temperatures up to 300^{o}C and forming rates up to 300 mm s^{-1} and, simultaneously to develop a robust experimental procedure for such data determination. The existing procedure given in ISO 12004-2:2008 standard was adapted to accommodate the desired temperature and strain rate ranges. Due to lack of in-situ access, the GOM ARGUS system was selected for strain measurement. The system measures changes in a pre-applied pattern (grid) after a test-piece has been deformed and does not required in-situ online access during forming.

2 Material and Experimental Method

As an internationally recognised standard exists (ISO 12004-2:2008), experimental methodology from that document was followed as closely as possible, but due to

the introduction of temperature and strain rate as variables, some modifications were required. These are detailed here.

2.1 Test material

Test-pieces were produced from commercial alloy AA5754, which offers good corrosion resistance, weldability and excellent formability. The material was supplied by Novelis UK Ltd in the form of 400 x 400 x 1.5 mm sheet, in the H111 condition. The essential Chemical composition of the alloy is shown in Table 1. At room temperature, it typically has a 0.2% proof stress of 100 MPa, a tensile strength of 215 MPa and an elongation of 25%.

Table 1 Major Elements in the Composition of AA5754

Element	Si	Fe	Mn	Mg	Al
Wt%	0.4	0.4	0.5	2.6 - 3.2	Bal

2.2 Test-piece geometry and test matrix

The geometry of the test-piece was a circular blank with a central parallel edged waist (Figure 1), based on ISO 12004-2:2008 standard. The rolling direction of the material was parallel to the longitudinal axis of the waist. According to the ISO standard, the length of the parallel waist section should be 25% to 50% of the diameter (D_p) of the punch used in the forming test. A hemispherical punch (in line with the Nakajima approach outlined in the ISO standard) was used in the current study, with a diameter of 80 mm. Therefore 30 mm was chosen for the length of the parallel section, which is equivalent to 37.5% of the punch diameter. The two 5.5 mm notches shown in Figure 1 are used for the alignment pins fitted on the blank holder to help centre the test-piece against the punch. Different widths of waist (W) were used to achieve notionally different strain paths which are shown by the points on the FLC curve in Figure 2.

Whereas aluminium alloys are generally insensitive to variations in strain rate typically experienced during metal stamping operations at room temperature, strain rate plays an important part in forming at elevated temperature. Therefore, FLCs for different temperature and strain rate are required for accurate simulation work at elevated temperature. Table 2 shows the test matrix of the forming speeds and temperatures investigated.

2.3 Gridding on test-piece surface

In order to use the GOM ARGUS system to analyse the strain after forming, a regular pattern was applied to the surface of the test-piece prior to forming. In the current work, a square pattern of 0.75 mm diameter circular dots with 1.5 mm centre-to-centre spacing was used. Gridding was carried out by electrochemical etching.

2.4 Forming test

A 250kN ESH high rate press was used for the forming tests. It has a maximum load capacity of 250 kN and a maximum controllable stroke of 100 mm, with a speed range of 0 - 5 m s^{-1}. An Instron furnace was mounted on the machine for the purpose of testing at elevated temperature. The tooling was mounted in the furnace and connected to a load cell outside the furnace via a stainless steel rod. An oscilloscope was connected to the control unit to record load and displacement.

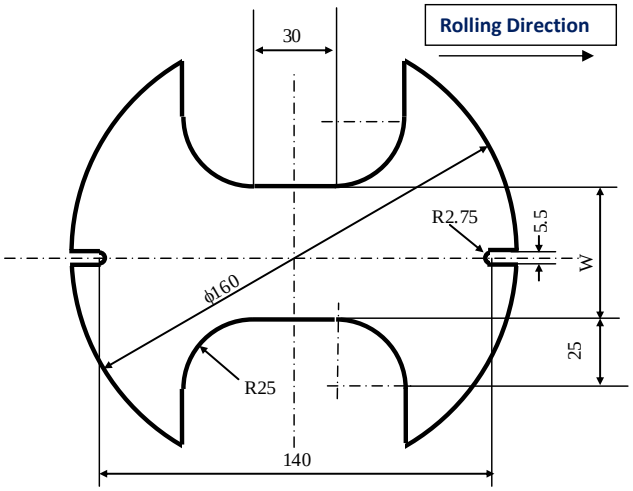


Figure 1 Blank geometry for Nakajima type tests (ISO 12004-2:2008) for Al alloys

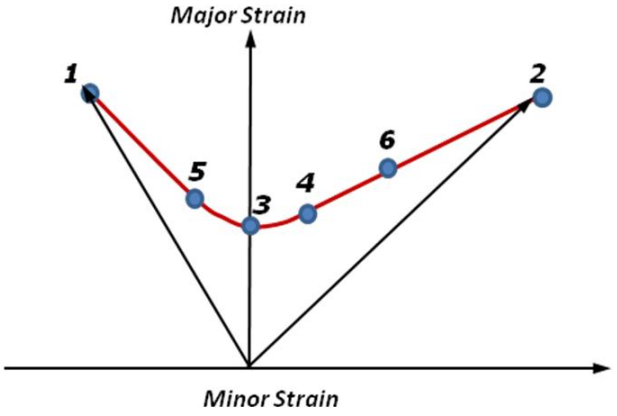


Figure 2 Schematic drawing of the test points for the FLC

Table 2 Test matrix for determining FLC

T (°C) / Speed (mm/s)	20	200	250	300
5	√			
20			√	
75		√	√	√
300			√	

Nakajima type tests were employed for the current work. The diameter (Dp) of the hemispherical punch used was 80 mm instead of the widely used 100 mm which is taken as an example in the ISO standard. However, it has been reported that the effect of punch size is insignificant even down to 1 - 10 mm range [20]. The hemispherical punch was fixed to the bottom plate of the tooling which was stationary during tests. The blank holders and test-pieces were driven downwards.

During forming test, a lubricated test-piece was placed on the blank holder in the heated furnace, and then formed when the temperature returned to the set value. Particular attention was paid to setting the final position of the stroke. Ideally, the punch should stop as soon as an incipient crack appears but this was seldom possible on the testing machine used. Adjustment to the final stroke position usually was necessary after each forming test. If the crack on the test-piece was too large, the stroke for the

subsequent (repeat) test, was reduced. Some of the test-pieces formed at 5 mm s^{-1} at room temperature (top row) and at 250 ^{o}C and 75 mm s^{-1} (bottom row) are shown in Figure 3.

2.5 Strain measurement

In-situ online measurement systems such as the GOM ARAMIS systems are often used to obtain strain distribution and limit strains in the FLCs at room temperature. For tests at elevated temperatures, however, online measurement using such systems might be difficult due to the restriction of access and viewing of the test-piece during forming. For this reason, another optical system, GOM ARGUS was selected for the current study. This system measures strain by comparing the pre-applied regular pattern before and after forming.

The GOM ARGUS system takes images from many different incident angles and computes local displacements to provide strain distribution. After computing strains in each sample, virtual sections perpendicular to the crack are constructed. The strain distribution of a No. 6 specimen formed at 20 ^{o}C and 5 mm s^{-1} is shown in Figure 4a, together with the virtual section lines. The strain profiles along the section lines are obtained and exported for data processing (Figure 4b).

2.6 Determining an FLC

Determination of limit strain values followed the ISO 12004-2:2008 standard. The exported strain profiles from GOM ARGUS analysis were processed and inverse parabolic fittings were made to obtain the limit strains. A pair of limit minor / major strains provides one point on the FLC chart. By analysing test-pieces with different geometry, data for different strain paths can be determined and hence an FLC is obtained.

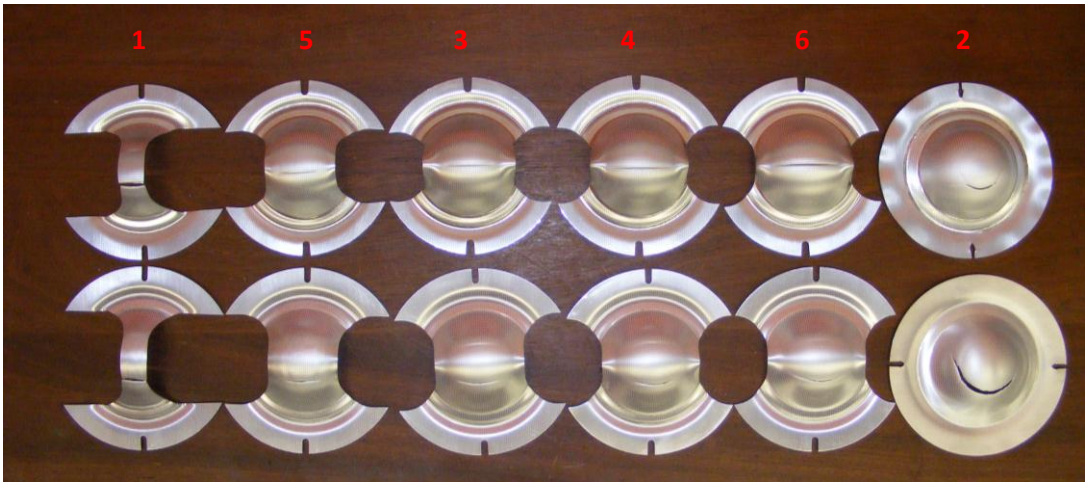


Figure 3 Test-pieces after forming at 20 ^{o}C, 5 mm s^{-1} (top row) and 250 ^{o}C, 75 mm s^{-1} (bottom row). The numbers at the top are for different strain paths indicated in Figure 2. From left to right: tensile to equibiaxial conditions.

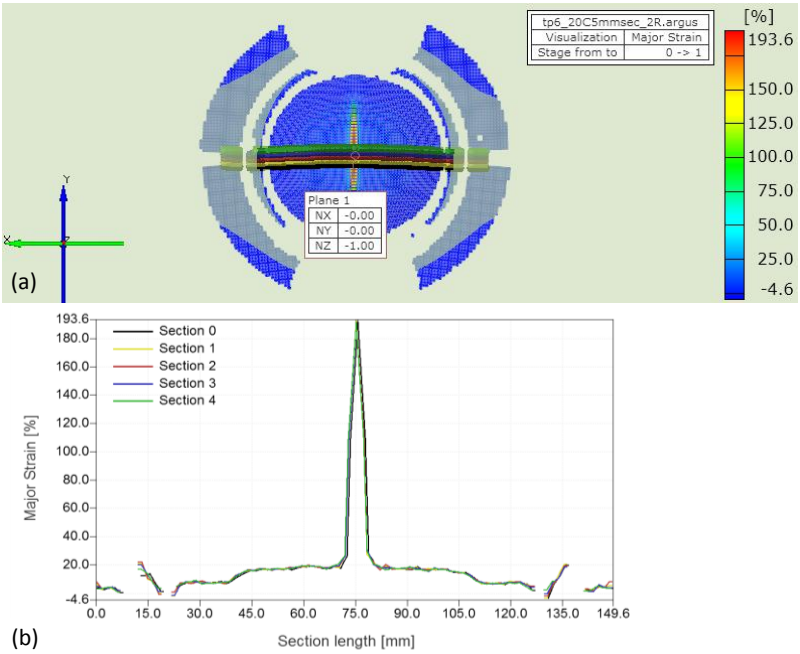


Figure 4 (a) Distribution of major strain and virtual cross sections perpendicular to the crack and (b) their strain profiles using GOM ARGUS software.

3 Results & Discussion

3.1 Effect of temperature on FLCs

Figure 5 shows FLCs for different forming temperatures, at a forming speed of 75 mm s^{-1}, except for the room temperature tests which are insensitive to strain rate, for which a speed of 5 mm s^{-1} was used. Generally speaking, formability increases with increasing temperature as evidenced by the shift up of the FLCs along the major strain axis. The increase is more significant at higher temperature. It is noticeable that there is little increase in forming limit between room temperature to 200°C, and that the increase in formability from 250 to 300°C is about twice the increase from 200 to 250°C in the plane-strain region. These results suggest that the warm forming temperature should be in the region of 250 – 300°C. As temperature increases, the V-shape of the FLCs appears to flatten, showing that the effect of the minor strain on formability reduces, although it is still significant at 300°C.

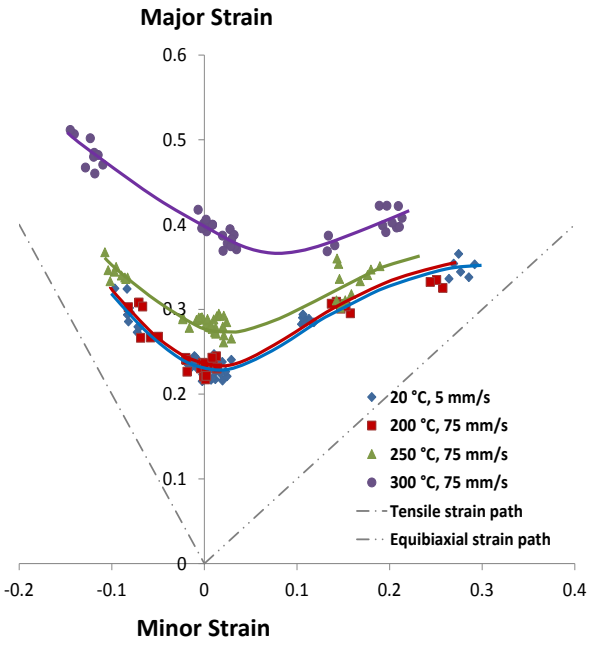


Figure 5 Effect of temperature on the FLCs of AA5754 at 75 mm s^{-1}.

3.2 Effect of forming speed on the FLCs

The effect of forming speed on the FLCs is shown in Figure 6 for the forming temperature of 250 °C. The forming limit increases with decreasing forming speed, suggesting that the best ductility lies at low speeds for warm forming. The effect of decreasing speed is therefore similar to that of increasing temperature. From Figure 6, it can be seen that when speed decreases from 300 mm s^{-1} to 75 mm s^{-1}, the forming limit increases in the plane strain region and the FLC curve is flatter. Significant improvement in forming limit is observed from 250 to 300°C. The increase in formability with decreasing strain rate is consistent with previous studies on tensile tests of the materials both in the current project and by others [21-22]. This trend is also consistent with study on FLC of AA5083 in the temperature range of 20-300°C [2].

Considering typical cold forming rates expected by industry, a compromise is needed for the selection of the most suitable forming speed. High speed is conducive to a high production rate, but low speed provides better ductility. It should also be remembered that the effects of forming rate and temperature are interrelated. To achieve similar ductility, one can use higher temperature with higher speed, or lower temperature with lower speed, for example, FLCs for 250°C / 20 mm s^{-1} and 300°C / 75 mm s^{-1} are at similar level. Both are significantly higher than the room temperature FLC.

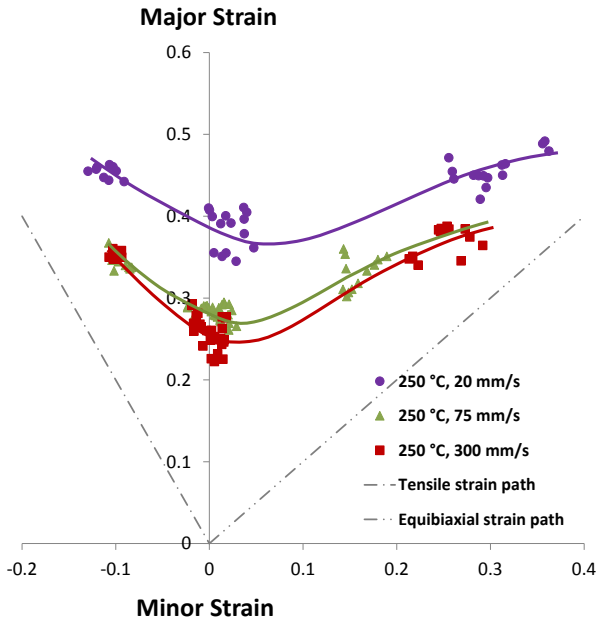


Figure 6 Effect of forming speed on the FLCs of AA5754 at 250 °C.

4 Summary & Conclusions

FLCs have been determined for AA5754 at different temperatures and different forming speeds, following a procedure based on the approach established by ISO 12004-2:2008 standard. The current approach used gridded test-pieces and the GOM ARGUS system to measure the strain after forming. Test-pieces with different geometries were designed and manufactured to provide different strain path during forming tests. The current study shows that forming test-pieces with a gridded pattern and analysing strain with an optical system provide an alternative route for the determination of FLCs. This is particularly useful for elevated temperature application where in-situ, online monitoring system often is difficult due to restricted/blocked viewing caused by the furnace. It was found that for AA5754, forming limit increases with increasing temperature and/or decreasing forming speed. The increase is more significant at higher temperature.

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