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Investigations on warm forming of AW-7020-T6 alloy sheet

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ABSTRACT

7000 series aluminium alloys have greater strength than conventional aluminium alloys used in the automotive industry, but little has been reported on their formability. In this paper the strength and formability of age-hardenable AW-7020 alloy sheet in the T6 temper condition was investigated at temperatures between 150 and 250 °C by warm tensile, Swift-cupping and cross-die deep-drawing tests. Differential scanning calorimetry (DSC) investigations were carried out to study the precipitation state of AW-7020 sheet in as-received, warm cross-die deep-drawn and post-paint-baked conditions. Formability was found to improve at temperatures above 150 °C and was sensitive to temperature and strain rate. There was also an onset of dynamic recovery from 150 °C. DSC results showed the presence of η' precipitates in T6 temper and that these coarsen during the warm cross-die deep-drawing and paint baking processes with ~30% drop in ultimate tensile and yield strengths. Dynamic recovery and coarsening of η' precipitates were found to contribute to the increase in formability at elevated temperatures.

1. Introduction

Automotive vehicles emit CO_2 gas due to fuel consumption and this leads to environmental pollution. Light-weighting of automotive vehicles helps to reduce the CO_2 emissions by reducing fuel consumption. The high bend stiffness and strength to weight ratio of aluminium alloys combined with their significant corrosion resistance and recyclability mark them as ideal candidates to replace their heavier steel counterparts in the automotive industry.

Despite all these advantages, aluminium alloys still lag behind in their application due to poor formability as compared to steels. Forming at elevated temperature has been widely recommended for aluminium alloys to tackle the poor formability. In general, elevated temperatures facilitate the forming process by reducing the yield strength and increasing the ductility. Therefore, it is important to understand the effects of elevated temperature on the forming behaviour of aluminium alloys.

A VW Golf V body-in-white prototype was developed in the European Super-Light-Car (SLC) project. This was based on an advanced multi-material design approach to use the best materials for appropriate functions, taking into consideration material and manufacturing costs, performance, recyclability and safety. Aluminium emerged as an innovative light-weight material of choice in competition with (new) steels, magnesium and plastics or composites. It achieves weight-saving of BIW parts up to 50% while maintaining safety and performance in a cost efficient way (Hirsch, 2011).

Medium strength AW-5xxx and 6xxx-series alloys are common and proven alloys for automotive structural parts and body-in-white (BIW) parts in European cars. However, for some key parts like the B-pillar, a higher level of strength to weight ratio is required to satisfy the roof crush and side impact standards. Schepers and Kelsch (2010) and Dörr (2011) investigated AW-7xxx alloys related to forming and crash performance, respectively. They reported that AW-7xxx-series alloys have potential to replace steel for structural components like A-pillar, B-pillar and side impact beams. Despite having potential AW-7xxx series alloys have been given little subsequent research attention for their use in automotive applications.

AW-7xxx-series alloys are age-hardenable alloys in which strengthening arises due to the formation of fine dispersed meta-stable precipitates during specific heat treatments such as T6. The sequence of precipitation of these meta-stable and stable phases in the ternary Al-Zn-Mg alloy has been reported by Degischer et al. (1980) and Löffler et al. (1983). They proposed a general precipitation sequence i.e. α-supersaturated solid solution-Al → GP Zones → η' → η-$MgZn_2$ or T-phase. Further Investigations by Deschamps et al. (2009) and Liu et al. (2010) found that the η' precipitate is the main strengthening phase in AW-7xxx alloy in the T6 condition.

The application of forming at elevated temperatures to age-hardening aluminium alloys requires knowledge of the interactions

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between temperature, exposure time, degree of deformation and precipitation kinetics. Kumar et al. (2013) found that AW-7020-T1 tube exhibits good formability when heated to 250 °C for 30 s and then deformed at strain rates ≥0.1 s^{-1}. Li and Ghosh (2004) investigated the tensile behaviour of age-hardenable AW-6111T4 alloys in the warm forming temperature range of 200–350 °C and in the strain rate range of 0.015–1.5 s^{-1}. They took the total elongation at fracture in the uniaxial tension test as a measure of formability. Total elongation was found to increase with increasing temperature and decreasing strain rate. Wang et al. (2012) studied the formability of AW-7075-T6 using uniaxial tension, bulge and swift cupping tests. They found that total elongation at fracture increased between 140 °C and 220 °C due to the increase in strain rate sensitivity which controls diffuse necking and prevents plastic strain from concentrating in a localized neck. They further reported that the best drawing and stretching formability can be realized at temperatures between 180 °C and 220 °C, respectively.

One of the major problems associated with forming at elevated temperatures is degradation of high strength temper of the age-hardenable aluminium alloys, as reported by Lee et al. (2004) and Torca et al. (2010) for AW-7075-T6 and AW-6082-T6, respectively. Temper further deteriorates during the paint baking heat treatment commonly applied in automotive industries to cure the paint, as reported by Sotirov et al. (2011) and Wang et al. (2012). They relate the temper deterioration mainly to dissolution and/or over-ageing of the main strengthening phase. However, no experimental evidence was reported. The main objective of the current work was to investigate the forming potential of AW-7020-T6 sheet.

2. Experimental

2.1. Tension testing at various temperatures

AW-7020-T6 sheet with a thickness of 2 mm and chemical composition (in wt.%) of 0.16 Si, 0.29 Fe, 0.08 Cu, 0.15 Mn, 0.93 Mg, 4.95 Zn, 0.01 Ni, 0.1 Cr, 0.04 Ti, 0.12 Zr was used in the current work. Tensile samples with a gauge length of 10 mm were machined from the as-received AW-7020-T6 sheet in the rolling direction as shown in Fig. 1(a). Tension tests were performed using a Bähr 805 A/D deformation dilatometer with a temperature and change in length resolution of ±0.05 °C and ±0.05 μm, respectively. Each tensile sample was heated by induction coil to the test temperature in 6 s and soaked for 4 s before each tensile test. Two horizontal fused silica push rods were attached to the sample within the gauge section and used to measure change in length during deformation. A detailed view of the deformation dilatometer and the test procedure are shown in Fig. 1(b) and (c), respectively. Tension tests were performed at temperatures between room temperature (RT) and 250 °C, and at strain rates between 0.001 and 1 s^{-1}. The tests were repeated at least three times to ensure reproducibility.

Important parameters from the flow curve measured during the tension test were determined as follows:

Yield stress = Stress at 0.2% offset true strain;
Peak stress = True stress at maximum load;
True uniform strain = True strain at point of tensile instability where $d\sigma/d\varepsilon = \sigma$;
True fracture strain = True strain at fracture, read from the flow curve.

2.2. Swift-cupping test

The Swift cupping tests were performed in an Errichsen Model 142-40-Basic universal sheet metal testing machine. An inside view of the machine showing the axially symmetric punch is given in Fig. 2(a). This test involves different deformation modes such as plane strain tension (in cup wall), bending (at punch and die corners), biaxial stretching (at cup bottom) and pure shear (in flange). Formability was determined using the limiting drawing ratio (LDR). This is defined as a ratio of initial blank diameter to the punch diameter. In this test the initial blank diameter is systematically increased at intervals of 5 mm until cracks appear in the drawn cup. The LDR is the ratio from the last sample tested before cracking occurs (Table 1).

Table 1
Test parameters for Swift cupping test.

Parameter	Value
Lubricant	Multidraw Drylube C1
Punch diameter	50 mm
Punch rounding radius	7 mm
Drawing ring radius	10 mm
Punch speed	800 mm min^{-1}
Blank holder pressure	1.1 MPa
Blank diameter	Variable; 90–125 mm (interval of 5 mm)
Duration of test run (heating + deep drawing)	<60 s
Punch temperature	Room temperature
Temperature in the forming zone (flange)	170, 200, 230 and 250 °C

Tests were carried out at temperatures between 170 and 250 °C. The die ring and the blank holder were placed inside an insulated container as shown in Fig. 2(b) and the lid attached. Next, the assembly was connected to an electronic temperature regulator that pre-sets the test temperature and displays the current measure temperature as shown in Fig. 2(c). The die ring and the blank holder assembly were then heated to the test temperature with cartridge heaters. Once the test temperature was attained the blank was placed at the centre between the die ring and blank holder as shown in Fig. 2(d). The full blank was assumed to heat up and reach the desired temperature very quickly (in seconds) as soon as it was in contact with the heated die ring and blank holder. To ensure the test occurred at the required temperature the whole assembly was quickly transferred in the test machine, and the test started immediately. Only the punch was kept at room temperature because it could not be heated and no control of the assembly temperature was possible during the drawing of blank. However, the thermal mass of the blank holder and die ring were sufficient to hold the blank at temperature for the duration of the test. When the punch first contacts the blank, the temperature of the blank decreases and therefore this part of the blank in contact with the punch was cooler than the rest of the blank (flange). Since the deformation is continuous, the portion of the drawn cup in contact with the punch continued to cool. However, the blank that is under the heated die ring and blank holder was still at the test temperature. Note that it was this region that was still at the test temperature that was being deformed.

2.3. Cross-die test

The cross-die test is a simulative test used by the automobile industry to evaluate the forming characteristics of sheet metals. In the current work cross-die tests were carried out at temperatures between RT and 250 °C on a hydraulic press as shown in Fig. 3(a). The initial blank was a square sheet of size 231 mm × 231 mm with chamfered corners as shown in Fig. 3(b). Temperature control was by an electronic temperature regulator that pre-sets the test temperature and displays the current measure temperature. Heating cartridges were used to heat the punch, blank holder and drawing die to the test temperature. When the test temperature was achieved, the drawing die, blank holder and punch temperatures were kept constant during the forming process.