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Warm deep-drawing and post drawing analysis of two Al–Mg–Si alloys

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ABSTRACT

The increasing use of aluminium alloys in light weight structural applications is restricted mainly due to their lower room temperature formability compared to steels. Forming at higher temperature is seen as a promising solution to this problem. In the present investigation two Al–Mg–Si alloys (EN AW-6016 and EN AW-6061) were deep-drawn at room temperature and 250 °C and their behaviour during drawing were compared. The effect of ram speed, drawing ratio, holding time, and temper was also investigated. Among the parameters investigated temperature was found to have the most significant effect on the force–displacement response. Because anisotropy has been an important concern during the deep-drawing process, this parameter was also investigated by looking at the earing profile. With increasing temperature the amplitude of earing decreased while the number of ears remained the same, indicating that there is no change in anisotropy with temperature. The cup thickness increases from the bottom of the cup to the flange with a local minimum around the mid-height of the wall.

1. Introduction

The demand for aluminium alloys has been increasing in brisk pace in recent years in automotive industries owing to their light weight and corrosion resistance. For instance, the use of aluminium sheet material for typical automobile body parts could provide a mass reduction of up to 50 pct compared to current steel construction. However, despite having high strength to weight ratio aluminium and its alloys are lagging far behind in this sector primarily because of their poor formability at room temperature, which is approximately 2/3 of that of steel as reported by Ayres and Wenner (1979). Improvement of formability is of special interest for the automotive industries, where weight reduction is compulsory on the one hand and panels have intricate shapes on the other hand. Super plastic aluminium alloys can address this issue by offering extremely high tensile ductility but with the drawback of high materials cost, low production rates and requirement of new forming equipment. Recent investigations on the phenomenon of increased tensile ductility of Al–Mg and Al–Mg–Si alloys showed a practical alternative to superplasticity. It has been documented by Flanigan et al. (1946) and by Li and Ghosh (2003) that the room temperature tensile elongation is at a minimum, as compared to both cryogenic and elevated temperatures. At cryogenic temperatures the increase of tensile elongation of many aluminium alloys is attributed mainly to the enhancement of work hardening and the same effect at elevated temperatures is principally due to increased strain rate hardening. Forming at elevated temperature seems one of the most promising solutions because forming at cryogenic temperature needs higher energy consumption and leads to increased spring back compared to elevated temperature deformation. The interest towards elevated temperature forming also derives from the reduction in flow stress, increase in ductility and increase in toughness of the material when compared with cold forming as illustrated by Abedrabbo et al. (2006).

Warm forming involves temperatures lower than those used during hot forging (approximately below 300–400 °C depending on the alloy composition) and consequently makes it easier to obtain close tolerance and high surface finish compared to hot forging. However, increasing formability by warm forming is still a challenge to the industry. This process is industrially more complex in terms of microstructure–mechanical behaviour relationship. In elevated temperature forming the most important issue is the selection of the temperature range. There should be very little structural change during operation. Hot forming might be

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accompanied by significant structural changes, though, associated with deformation-induced recrystallization and growth of grains or particles. In addition, creep may affect the forming deformation and cavitations at the grain boundaries can lead to permanent failure at low strain rate. So, warm forming is preferable for aluminium alloys compared to hot forming in order to improve the formability.

Forming of aluminium alloys at elevated temperatures has already been reported by many researchers. Finch et al. (1946) investigated the potential of warm forming by deep drawing of both rectangular and circular cups from annealed and hardened aluminium alloy sheets as early as in 1946. Their results showed significant improvement in the drawability (in terms of cup height) at a relatively moderate temperature of about 150 °C even for the precipitation hardened alloys (like 2024-T4 and 7075-T6). In the 1950s an aluminium alloy containing 3–4% Mg was generally employed for warm press forming panels for the most expensive ranges of cars. It was observed by Shehata et al. (1978) and by Ayres and Wenner (1979) that the cup height increased with increasing forming temperature and/or decreasing punch speed for an Al–2% Mg and 5182-O alloy. Warm forming of alloy 5182-O at 120 °C was successfully used by General Motors (Ayres and Wenner, 1978) to produce inner door panels and a V-6 oil pan at commercial press speeds, by heating both the die and the blank and using a mica lubricant and a MoS_2/graphite release agent. According to their results, some precipitation hardened alloys could also be warm formed successfully at 250 °C to produce components at a cycling rate of 5 parts/min. The optimum forming temperatures were found to be 200 °C and 250 °C for the precipitation hardened and the strain hardened alloys, respectively. In a more recent study with 5083, Naka and Yoshida (1999) found that the limit drawing ratio increases with increasing die temperature and decreases with increasing forming speed. Bolt et al. (2001) also conducted comparative warm drawing tests on 5754 and 6016. They found that the minimum die temperature required for a significant deeper product is lower for the 6016-T4 compared to 5754-O alloy. At a temperature of 175 °C the increase in maximum height for 6016-T4 is 30% while it was only 11% for 5754-O. They also concluded that warm forming offers a good possibility for drawing complicated aluminium sheet products which cannot be made at room temperature without extra forming or joining operation.

Although 5xxx series alloys exhibit higher strength than 6xxx alloys in annealed condition they suffer from the problem of dynamic strain ageing and the resulting stretch marks, which affect the surface quality. Also they are not heat treatable and can only be hardened by mechanical working. 6xxx alloys have the advantage of being free of Lüdering. This arises from the lower Mg content compared to the 5xxx series. Other solute elements such as Si and Cu are either energetically bound to Mg in the form of coherent clusters or have too low diffusion rates to enable the formation of effective solute atmospheres that pin dislocations. 6xxx alloys also have the advantage of being heat treatable. After solution heat treatment they show low yield strength (<130 MPa) and good formability that gives low springback and relative ease for production of complex parts with high dimensional accuracy. In service, though, there is a demand for higher yield strength (>200 MPa). These alloys harbour a huge potential for improvement of strength by precipitation hardening during the paint baking cycle, typically of the order of 220–275 MPa, after paint baking at 170–200 °C for times up to 30 min (Ayres and Wenner, 1979). Typically 5xxx alloys are used for inner panels because of their better formability and 6xxx alloys for outer panels because of the absence of stretcher lines. It would be, however, preferable to use only one type of alloy for the all applications. The prospect of extending the applications of 6xxx alloys in the automotive industry has renewed the interest in Al–Mg–Si–(Cu) alloys in recent years. It also drives the demand for new solutions to improve their formability and warm forming is one of the promising processes. The examples presented above showed that most of the previous investigations on warm forming focussed on 5xxx alloys. Recent experiments with 6xxx alloys also gave promising results in terms of enhanced ductility at elevated temperatures with the added advantage of precipitation hardening. However, these results are limited and there is still the need for a more systematic study of the effect of the material and process parameters on warm forming process.

Table 1
Composition [wt%] of the as-received materials.

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Other
6016	1.03	0.25	0.06	0.15	0.42	0.02	<0.15
6061	0.62	0.35	0.20	0.08	0.95	0.15	<0.15

Deep drawing is an important and popular process in the assessment of formability of sheet metals and has been used in the current investigation to explore the warm forming potential of 6xxx aluminium alloys. Two 6xxx aluminium alloys, EN AW-6061 and EN AW-6016, were selected and deep drawn either at room temperature or at 250 °C. Al–Mg–Si alloys with no or very little Cu are the materials of choice in Europe and 6016 is considered as the most promising system as explained by Kleiner et al. (2001), while alloys with higher Cu content, as 6061, are preferred in North America. The age-hardening response of these alloys is very significant and hence the control of precipitation during thermo-mechanical treatment is critical for obtaining an optimal alloy performance. Therefore, the influence of several deep drawing parameters as temperature, ram speed, drawing ratio, holding time at drawing temperature before drawing and friction as well material parameters as temper condition and alloys chemistry has been investigated. The punch force evolution during drawing has been measured. The plastic anisotropy response of the materials, which can be directly reflected by the earing behaviour of the drawn cups, has been traced in the present investigation by measuring the foot prints.[1] The thickness variation along the cup is also an important parameter as extensive thinning can result in tearing. The thickness distribution along a line running from the bottom to the flange was then also measured for the above mentioned conditions.

2. Experimental procedure

2.1. Material

Aluminium alloys EN AW-6016 and EN AW-6061 in the form of rolled sheets were used for the present research. The sheets had been previously cold rolled, solution treated, quenched and naturally aged (T4 temper). The thicknesses were 1.0 and 1.2 mm respectively. T6 temper was made directly from T4 by heating T4 material at 150 °C for four hours followed by 170 °C for four hours in oil bath and subsequently quenched in water. The chemical compositions of the alloys are given in Table 1.

Alloy 6016 is a Si excess alloy (Mg/Si = 0.4; with Mg and Si expressed in wt.%) while alloy 6061 is almost balanced (Mg/Si = 1.5). Another noticeable difference between the two alloys is the higher Cu content of alloy 6061.

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[1] Equivalent to earing, i.e. a wavy projection formed at the open end of a cup or shell in the course of deep drawing because of differences in directional properties. Also termed as scallop. An important consequence is inhomogeneous distribution of mechanical properties and wall thickness due to volume conservation.