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INHOMOGENITIES OF PLASTIC DEFORMATION – SERRATIONS IN COMERCIAL Al-Mg ALLOYS

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Abstract: *Plastic deformation of solid solutions is often accompanied by plastic instabilities due to dynamic strain aging (DSA) and dislocation interaction. The dislocation interactions lead to stress serrations and localized strain (deformation bands) in tensile tests, known as the Portevin-Le Chatelier (PLC) effect. The instable PLC deformation is closely connected with a localization of strain within the front of (propagating) deformation bands. These bands significantly limit the sheet formability leading to unacceptable surface roughness or premature fracture.*
The characteristics of serrated yielding of commercial Al-Mg sheets (3-6%Mg) have been studied using room temperature tensile testing. Tensile tests were performed at strain rates of $\dot{\varepsilon}_1 = 6.7 \cdot 10^{-4} s^{-1}$ *and* $\dot{\varepsilon}_2 = 6.7 \cdot 10^{-3} s^{-1}$. *The initiation of serrated flow was found to depend on Mg content as well as strain rate. The type of the serrations also, was governed by the strain rate and Mg content. The amplitude of the serrations (*$\Delta\sigma$*) increased with increasing strain and decreasing strain rate. The noticed dependence* $\Delta\sigma$ *of the Mg content reflects the role of Mg atoms in locking/pinning the dislocations. The strain rate showed no influence on the yield stress, while the general stress level and ultimate tensile stress have increased with decrease of strain rate. Therefore, it leads to increase the difference between ultimate and yield strength (*R_m-$R_{0.2}$*), and stronger work hardening effect, because of suppression of the dynamic recovery in Al-Mg alloys.*

Keywords: *Al-Mg alloys, serrated yielding, Mg content, strain rate, The Portevin-Le Chatelier effect (PLC).*

1. INTRODUCTION

Lightweight Al-Mg alloys have been widely used in many fields because of their optimal combination of strength, formability, corrosion resistance and weldability. However, their unstable plastic flow restricts theirs application. Unstable flow appears as a yield point elongation (or Lüders elongation) within the few percent of deformation, and discontinuous or serrated yielding at higher strains, tipical for industrial production. The Lüders elongation during uniaxial stretching causes the appearance of surface relief known as "A" ("flamboyant"), as discontinuous yielding causes the appearance yielding "B" ("parallel bands") type surface markings [1-4]. Both stretcher markings are harmful because they cause pronounced surface roughness.

Discontinuities in the flow stress as a manifestation of dynamic strain ageing, are commonly observed during deformation of f.c.c. solid-solution aluminum alloys under certain circumstances. It has been extensively investigated in aluminium alloys containing magnesium [5-10]. In the most accepted models serrated flow is related to the dynamic interaction between diffusing solute atoms and mobile dislocations, i.e. dynamic strain ageing (DSA). Solute atoms restrict the mobility of the dislocations and make dislocation rearrangement and annihilation more difficult. Mg atoms are particularly effective in this because of their large atomic size difference with aluminium. Solutes preferentially concentrate at dislocations due to the energetic interaction of the two sources of field, forming solute atmospheres at mobile dislocations and arrest them. When the applied force is raised high enough, the mobile dislocations break away from the atmospheres and advance to the other obstacles. Repetition of this process is manifested as the serrated flow observed in the stress-train curve. The amplitude of the serrations, defined as the stress change from the highest to the lowest points of the serration, is used for evaluated /the main measure of the serrated yielding.

Different serrations types can be identified from macroscopic stress-strain curves as a result of differences in microstructural strain localization./microstructure and testing condition. Researches classify serrations as type A, B, C D or E, which can occur sometimes simultaneously, depending on the testing condition [2,10-11]. Different types of serrations can overlap each other. Type A serrations are characterized by an abrupt rise of loads (stresses) above the general level of the load-extension (stress-strain) curve, type B are marked by fluctuations loads around the general level of curve, and type C serrations are characterized by fall of loads below the general level of curve. In many cases it is not clear to make distinction between B and C serrations. It seems that C serrations drop to lower stresses more abruptly than B serrations and A and B serrations do not occur under the some test conditions [6,9,12] More recently a laser scanning extensometer was used to identify serrations types based on deformation band propagation [13-15]. Detailed description of serrations types was done in ref 7.

In order to describe the amplitude of the serrations ($\Delta\sigma$), defined as the stress change from the highest to the lowest points of the serrations, has been investigated [6,16-20].

The strength of Al-Mg alloys arises from several factors. The Mg in solution provides solution hardening, and these alloys also have a significant Hall-Petch slope compared with other Al alloys, so grain size strengthening is important. The strain hardening significant contributes to the strength because of the high work hardening rate. Apart well known influence Mg content on the mechanical properties, it would be expected that Mg content has influence on deformation behaviour and the characteristics of serrated yielding. Further, it is known that deformation behaviour and mechanical properties of Al-Mg alloys are sensitive to strain rate.

The present paper is focused on some experimental observations of characteristics of serrated yielding in three commercial magnesium-containing aluminium alloys as function of deformation variables.

2. EXPERIMENTAL

To investigate the influence of Mg content and the strain rate on the deformation behaviour, three annealed commercial Al-Mg alloys, with average grain size of approximately 15 μm were tested. The chemical compositions of the alloys are:

AlMg3 (3.1 Mg, 0.03 Mn, 0.31 Fe, 0.09 Si); AlMg4.5Mn (4.55 Mg, 0.47 Mn, 0.42 Fe, 0.16 Si), AlMg6Mn (5.95 Mg, 0.54 Mn, 0.36 Fe, 0.12 Si).

Tensile tests were carried out at room temperature on a “Zwick” testing machine, using small ASTM tension specimen with a 25 mm gauge length. To investigate the influence of the strain rate on the mechanical properties and serrated yielding, different initial strain rates of $\dot{\varepsilon}_1 = 6.7 \cdot 10^{-4} s^{-1}$ and $\dot{\varepsilon}_2 = 6.7 \cdot 10^{-3} s^{-1}$ were applied.

3. RESULTS

The set of typical deformation curves of annealed Al-Mg alloys with grain size of about 15 μm, are shown in Figs. 1 and 2. Well developed serrations have been observed in all investigated alloys. The critical strain for serrated yielding ε_c=0, i.e. serrations began immediately after the Lüders elongation and continued until failure. The amplitude of the serrations beyond the Lüders strain increases with strain. During initial deformation at lower strain rate ($6{,}7\cdot10^{-4}s^{-1}$) A+B types of serrations were observed, and with increasing strain they changed to type B. This behaviour was observed in both AlMg3 and AlMg4.5 alloys. Type C was observed in AlMg6Mn alloy at the same strain rate (load falls below the general level of the curves).

With increasing strain rate, at strain rate of 6,7·10-3 s-1, in AlMg3 alloy the type A serrations were observed, while A, A+B and B serrations were observed in the other two alloys (Fig. 2). Despite that A and B serrations occur in both alloys, type A serration is less prominent in AlMg6Mn than in AlMg4.5Mn alloy, i.e. type B dominates in the AlMg6Mn alloy. The amplitude of the serrations steadily increases as a function of strain in all cases.

Apart from difference in the type of the serrations, there is also a difference in the amplitude of serrations, $\Delta\sigma$ (Fig. 3) shows the maximum amplitude of the serrations, $\Delta\sigma$, as a function of strain rate and Mg content. $\Delta\sigma$ depends strongly on both Mg content and strain rate. As the Mg content increases, amplitude of the serration raises almost linearly, while the increase of strain rate decreases it.

The effects of the strain rates and Mg content on the mechanical properties are shown in Fig. 4. Ultimate tensile strength slightly increases with decreasing strain rate and increases with increase in Mg content.

4. DISCUSSION

Lüders yielding and serrated flow were established to confirm the inhomogenous deformation during uniaxial tension. The Lüders yielding at the onset of plastic flow in the annealed condition in tested Al-Mg alloys indicates a low initial density of mobile dislocations. The Lüders yielding in substitutional alloys, like Al-Mg, occures when concentration of solutes atoms is enough to form atmosperes around the mobile dislocation and block them. To continue deformation the dislocation have to break away from these atmospheres and multiply.

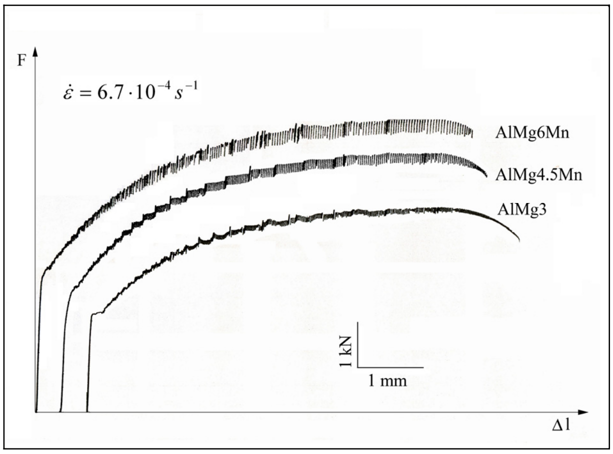

Figure 1. Deformation curves of Al-Mg alloys at strain rate $\dot{\varepsilon}_1 = 6.7 \cdot 10^{-4} s^{-1}$.

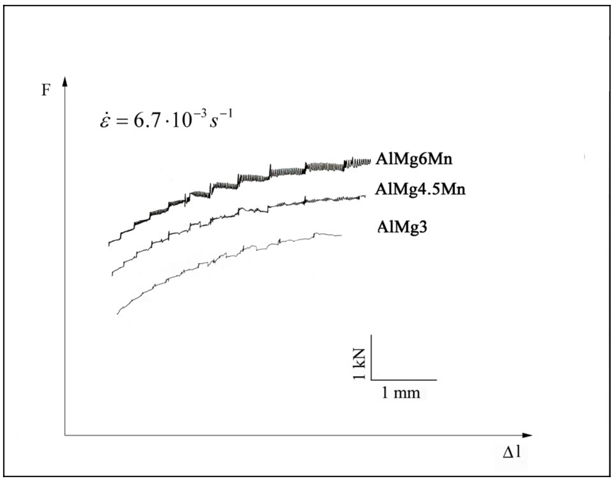

Figure 2. Deformation curves of Al-Mg alloys at strain rate $\dot{\varepsilon}_2 = 6.7 \cdot 10^{-3} s^{-1}$ - segment with serrations.

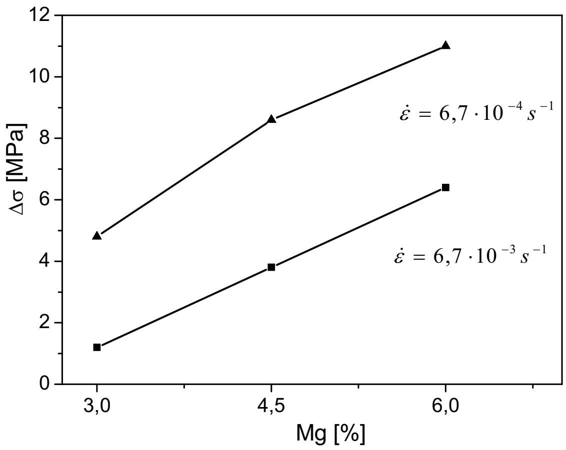

Figure 3. The influence of magnesium content and strain rate on amplitude of serrated yielding (Δσ).

So, the Lüders yielding fenomenon depends on relation between concentration of solute atoms and dislocation density [21], and become more pronounced with increasing of this relation [10].

The absence of Lüders yielding was observed only in AlMg6Mn alloy with coarse grains [22] at both strain rate (similar results was published earlier for AlMg6.5 alloy with grain size of 35-40μm ref. 12). This apparently is due to both the higher Mg content and large grains. The addition of Mg increases density of mobile dislocations, produced in activated dislocation sources [8,10]. This activation of dislocation sources is enhanced in large grains structures, together with the spreading of deformation to neighbouring grains. This suggest that the high density of dislocation in coarse grained AlMg6Mn alloy is sufficient to remove yield point (inhomogenities) observed in the other two alloys. The serrated yielding has occurred in all investigated alloys under the testing condition and also increases from AlMg3 to AlMg4.5Mn and than AlMg6Mn alloys (Figs 1 and 2). Mg content and strain rate affect the type and frequency of the serrations, but the influence of the grain size was not observed.

At low strain rate tests (~10-4s-1) type A+B and B serrations occure in both AlMg3 and AlMg4.5Mn alloys, but in AlMg6Mn alloy only C type occures. At higher strain rate (~10-3s-1), while the A type serration dominates in AlMg3 alloy, with further increase in Mg content type A become less prominent, resulting in the domination of type B serrations. This difference is related to the Mg content. Obviously, the increase of the Mg content as well as decrease of the strain rate lead to changes types of serration on the stress-strain curves from A→B→C. It seems that when the arrest mobile dislocation become more effectively, as a result of addition Mg and lower strain rate, it leads to change of types of serrations from A via B to C. C type of the serrations only fall below the general stress-strain dependence and it is considered that this type refer to the unlocking of dislocations from solute pinning and called “unlocking” serrations. On the other hand type A or B serrations refer to the locking of dislocations by solutes and called “locking” serrations. That kind of relationship has been found in ref. [9,12,20]. It seems that the most effective impede of dislocation and consequently the highest flow stress (Fig. 4) corresponds to the appearance of the type C of serrations, but/although the exact mechanism leading to either A and B or to C serrations are still hardly known.

The intensity of the serrated yielding, evaluated by the amplitude of the serration, has showed a relatively strong dependency of the Mg content and strain rate (Fig. 3). The moving dislocations are temporary held at obstacles, so Mg atoms than diffuse to these dislocations and arrest them. It was shown that both the mobile and forest dislocations densities increase with increasing Mg content [8,10 Horvath, Robinson]. Moreover, the increases of the mobile dislocation is higher than forest dislocation, because Mg enhanses strongly the multiplication of mobile dislocations. The addition of Mg decreases the mean free path for dislocation motion, so the dislocations intersect each other more frequently. Also, the addition of Mg suppresses the recovery of the Al-Mg alloys because the stocking fault energy decreases and cross-slip becomes more difficult [21]. This enhances strongly the multiplication of the mobile dislocations, leading to theirs higher density. The more dislocations temporary held at obstacles, the higher force is needed for dislocation unpinning, resulting in higher amplitude of the serrations on the stress-strain curve [1,5,10,20,23-25].

Strain rate analysis gives a good indication of the intensity of dynamic strain ageing, too. It is assumed to be due to lower rate of mobile dislocations, which is proportional to strain rate [21]. Therefore, the waiting time for the mobile dislocations at obstacles is longer which is manifested as an increase of the amplitude of the serrations. The mobile dislocations can be arrested more effectively by solute atoms at lower strain rate ($\sim 10^{-4}$ s^{-1}) than at higher ($\sim 10^{-3}$ s^{-1}), leading to the increase of the amplitude of the serrations.

It was found that the yield stress is rather strain rate independent in annealed Al-Mg alloys. On the other hand the ultimate strength exhibits inverse strain rate dependence. At higher strain rate the level of flow curves decreases. The minor influence the strain rate on the yield stress indicates that the concentration of the solutes /Mg atoms / in annealed Al-Mg alloys (3-6 wt.%Mg) is sufficient to form atmosphere and block mobile dislocations at the onset of the deformation and the stress for unpinning dislocation i.e. multiplication mobile dislocations is independent of the strain rate. The strength of the tested Al-Mg alloys in annealed condition is affected primarily by solution strengthening/hardening from the Mg (and/or other) atoms and grain size strengthening, according to the well known Hall-Petch relationship [21]. According to the previously reported results, the frictional stress σ_0 in the Petch equation, which reflects solution hardening due to Mg in solution, increases linearly with Mg content [23]. The addition of approximately 0.5wt. % Mn increases strength of AlMg4.5Mn and AlMg6Mn alloys, mainly due to solid solution strengthening.

5. CONCLUSIONS

Deformation behaviour has been investigated in three annealed commercial Al-Mg alloys (AlMg3, AlMg4.5Mn, and AlMg6Mn) at room temperature and strain rates of 6,7·10-4 s-1 and 6,7·10-3 s-1. Well developed serrations have been observed in all investigated alloys. The instable PLC deformation is closely connected with a localization of strain within the front of (propagating) deformation bands. These bands significantly limit the sheet formability leading to unacceptable surface roughness or premature fracture.

Serrations of A, B, A+B and C types were observed on stress-strain curves. The type and frequency of serrations were governed by Mg content and strain rate. While the A type serration dominates in AlMg3 alloy, further increase in Mg content decrease it, resulting in the domination of type B serrations in higher strain rate or tests C type in low strain rate tests in AlMg6Mn alloy.

The intensity of the serrated yielding, evaluated by the amplitude of the serrations/stress drop, ($\Delta\sigma$), increased with increasing strain and decreasing strain rate. The noticed dependence amplitude of the serrations of the Mg content reflects the role of Mg atoms in locking/pinning the dislocations.

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