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The Effect of Strain-Rate Sensitivity on Formability of AA 5754-O at Cold and Warm Temperatures

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Aluminum-magnesium (Al-Mg) alloys have been widely used in diverse applications ranging from automotive bodies to food processing industries because of their excellent high-strength-to-weight ratio, corrosion resistance, and recyclability potential. The formability of these alloys is decreased at room temperature (RT) and is related with the strain-rate sensitivity. This study presents the effect of strain-rate sensitivity on formability of AA 5754-O alloy sheet at a test temperature range of −60 to 250 °C by duplicate tensile test at different strain rates. The test results indicated that the formability change with positive or negative strain-rate sensitivity values. It was observed that the strain-rate sensitivity values increased at negative temperatures with respect to RT. The best formability condition for this alloy in the test ranges was observed at 250 °C and 0.0016 s^{-1}.

Keywords AA 5754-O, Al-Mg alloys, formability, Portevin-Le Chatelier (PLC) effect, strain-rate sensitivity (*m*)

1. Introduction

AA 5754-O alloy which is one of the 5XXX series non-age hardenable aluminum-magnesium (Al-Mg) alloys and is denoted as Al 5754, Al-Mg5754, or Al-3%Mg in the global market. Magnesium is the major alloying element in this alloy. The alloy has been widely used in the production of automotive interior panels. These materials have been receiving considerable scientific and technological attention because they show little or no progressive damage accumulation prior to fracture (Ref 1). The formability of Al-Mg alloys is poor at room temperature (RT) by comparing with low carbon steels and with the same alloy formability at elevated temperatures. The poor ductility of these materials can be improved by increasing the forming temperatures or by changing the material chemical and phase composition (Ref 2, 3). At the same time, the ductility of Al-Mg alloys decreases with increasing the Mg content (Ref 4).

The strain-rate sensitivity (*m*) is defined as the derivative of flow stress with respect to the strain rate (Ref 5). *m* is a very important material property in the forming processes to describe the ability of the alloys to resist necking (Ref 6) and has two important effects. The first effect is the increase in flow stress value with increasing of the testing speed, and the second one is the delay in the onset of diffuse necking (Ref 7). The strain-rate effect must be taken into account in the design of automotive components, especially the structural components. Although thinner steel with a positive *m* value can be used for crash parts, the part with improved strength must not be too strong or stiff. The responses of strain-rate sensitivity to strain for the various aluminum alloys are different. Experimental results indicated that two possible phenomena were mentioned. One is the dependence of strain-rate sensitivity on strain. The other one is variation of strain-rate sensitivity with strain rate (Ref 8).

Although most materials exhibit positive strain-rate sensitivity in which the flow stress increases with the strain rate such that *m* is greater than zero, some of the alloys show negative strain-rate sensitivity. Negative strain-rate sensitivity causes repeated strain localization which is referred as dynamic strain aging (DSA). Strain localization leaves an undesirable stretcher line on the surface of the final product. This phenomenon was first introduced by Portevin and Le Chatelier (PLC) (Ref 5, 9). The deformation Al-Mg alloys at RT is discontinuous because of PLC effect (Ref 10). This behavior can be explained by the interaction between dislocations and solute atoms. The hampered dislocation movement by the solute Mg atoms leads to a higher initial yield stress. At low-strain rates, dislocations move slowly and the solute atoms can migrate to the dislocations while they are arrested at other obstacles or solutes (Ref 11). However, when the average arrest time is short at high-strain rates, the clusters are too small to produce an effective enhancement of the strength of the obstacle and the PLC effect is not observed (Ref 12). The PLC effect leads to the formation of deformation bands that not only leave undesirable traces on the surface of the final product, but also reduce the ductility of the alloy (Ref 13-15). Numerous studies have been performed on the PLC effect in Al-Mg alloys including both experimental investigations and numerical modeling (Ref 10, 16-22). However, there are limited research in the literature on the relationship of PLC bands and tensile instability (Ref 13, 15). Also, no quantitative data have yet been reported to address the relationship between PLC strains and PLC markings. Meanwhile, numerous efforts have been made to deal with the effect of surface roughness on formability of aluminum alloys (Ref 21, 22). Although most studies of the plastic deformation

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of Al-based alloy systems available in the literature have been carried out at room or elevated temperatures, there is an interest in understanding work-hardening behaviors of commercial alloys at lower temperatures not only because of the fundamental nature of such studies, but also from the practical side as many of these systems are restricted from being used at elevated temperatures (Ref 23-25). The mechanical properties of these materials have not been sufficiently explored for low-temperature regime (Ref 26). Halim et al. (Ref 10) investigated the effect of strain-rate sensitivity on the PLC at −50 °C and RT for AA 5754 alloy. The experimental results showed that both of the PLC behavior and the flow stress decrease with increasing the strain rate. This finding was explained by a negative value of *m* found at RT. The value of *m* becomes slightly positive at −50 °C (Ref 10). A formability investigation about the effect of strain-rate sensitivity on theoretical prediction of limiting draw ratio (LDR) for cylindrical cup drawing process was performed for this alloy by Narayanasamy et al. (Ref 27). They determined the rate of decrease in LDR value with respect to the value of coefficient of friction which is high for higher values of strain-rate sensitivity. They also observed that the LDR value decreases with increasing the yield stress for various strain-rate sensitivity values.

In this study, the effect of strain-rate sensitivity on formability of AA 5754-O is investigated experimentally in the range of temperature −60 to 250 °C and strain rate 0.0016 to 0.04 s^{-1}.

2. Experimental Procedure

2.1 Material

AA 5754-O as received alloy with a thickness of 1.82 mm produced by Alcan was used for this study. Table 1 gives the chemical compositions of AA 5754-O alloy which was measured by Spectromax. Test specimens were prepared according to ASTM E8 standard (Ref 28) along the rolling direction by using water jet cutting machine to prevent thermal effects on the material cutting surfaces. The mechanical properties of AA 5754-O alloy measured at RT and 0.0016 s^{-1} strain rate are given in Table 2.

2.2 Test Procedures

The uniaxial tensile tests were performed on the alloys between −60 and 250 °C. The low temperatures (below RT) were achieved by supplying liquid nitrogen to the chamber. Gauge lengths on the test samples were measured by a video-type extensometer measurement system. This system was located outside of the chamber to eliminate the effect of test temperature on the measurements. Samples were tested at seven different temperatures: −60, −30, 0, 25 (RT), 100, 175, and 250 °C, respectively. Three strain rates (0.0016, 0.008, and 0.04 s^{-1}) were applied on the samples. It is very important to get stretcher marks free surface. For this reason, the PLC effect range was determined. For each test temperature and strain rate, each test was repeated at least for three times to get statistically meaningful results.

There are two methods commonly used to evaluate strain-rate sensitivity. The first method is called as duplicate test method. In this method, tensile test is performed using two different specimens at different strain rates and two true stress-true strain diagrams were determined. From two diagrams, *m* is calculated using Eq 1. The second method is known as "Jump rate test" where the crosshead speed is increased to produce a jump in the strain rate at a predetermined level of strain (Ref 28). In this method, strain rates were changed during the tensile test. In this study, the duplicate test method was used for strain-rate sensitivity calculation using strain-rate pairs of 0.0016 and 0.04 s^{-1}.

Strain-rate sensitivity values were calculated using true stress-true strain diagram by Eq 1.

$$m = \log(\sigma_2/\sigma_1)/\log(\dot{\varepsilon}_2/\dot{\varepsilon}_1) \quad \text{(Eq 1)}$$

3. Results and Discussion

The effect of strain-rate sensitivity on true strain and ductility was investigated by testing the samples at temperatures between −60 and 250 °C. The PLC effect range was determined for all test conditions. Figure 1(a-c) shows the variation of PLC range with true stress-true strain curve at various strain rates and temperatures. Figure 1(a) indicates that the PLC has appeared at all temperatures below 175 °C for 0.0016 s^{-1} strain rate. However, the PLC was seen in the range of −30 to 175 °C at 0.008 s^{-1}, and 0.04 s^{-1} strain rates (Fig. 1b-c). The higher deformation speed eliminates the PLC at negative temperatures. As seen from Fig. 1, no stretcher line was observed at 175 °C and 0.0016 s^{-1} and −60 °C and 0.04 s^{-1}. When the *m* value becomes negative, the loss stability of the material and appearance of the PLC effect exists (Ref 28). Strain-rate dependence of flow stress is more considerable at high temperatures.

The variation of the *m* value with true strain was measured at cold and warm temperatures as shown in Fig. 2 and 3, respectively. Strain-rate sensitivity was calculated at strain rates between 0.0016 and 0.04 s^{-1} using the first method. Although the strain-rate sensitivity was negative at RT and 0 °C, it is positive at −30 and −60 °C. This could be an indication of ductility increase. The variation of *m* value is almost constant at −30 °C. However, the strain-rate sensitivity decreased with

Table 2 Mechanical properties of AA 5754-O at room temperature

E, GPa	UTS, MPa	YS, MPa	TE, %
66	291	111	24

Table 1 Chemical compositions of AA 5754-O (in wt.%)

Element:	Al	Mg	Mn	Fe	Si	V	Cu	Ti	Others
Wt.%	Balance	3.17	0.51	0.163	0.112	0.0098	0.0096	0.009	<0.003

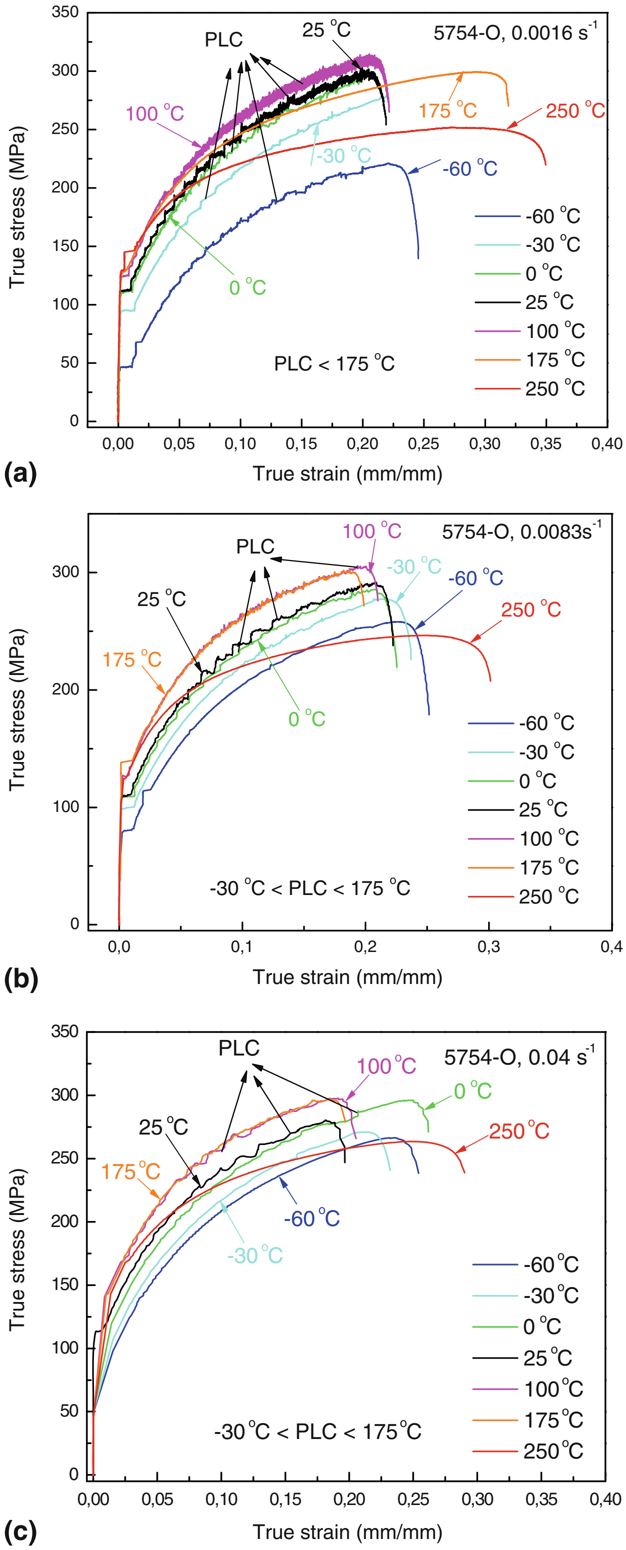

Fig. 1 PLC range at various temperatures (a) 0.0016 s^{-1}, (b) 0.0080 s^{-1}, and (c) 0.04 s^{-1}

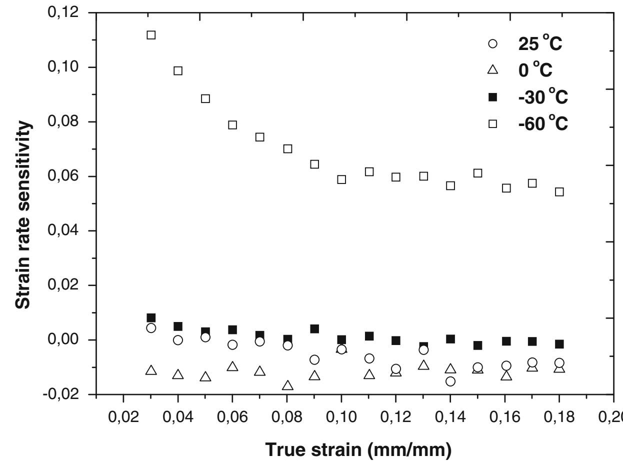

Fig. 2 Strain-rate sensitivity vs. true strain at the range of −60 to 25 °C

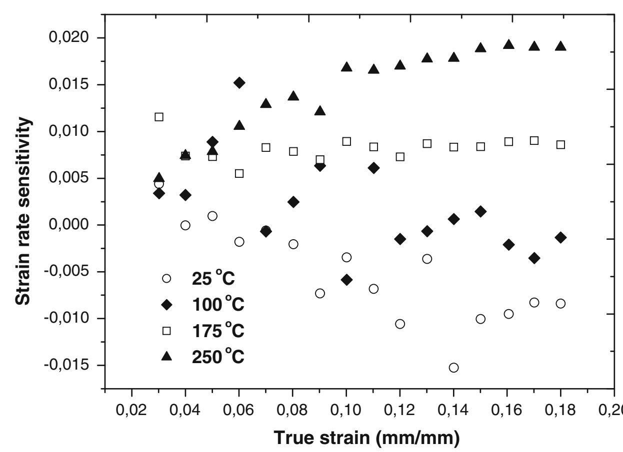

Fig. 3 Strain-rate sensitivity vs. true strain at the range of 25 to 250 °C

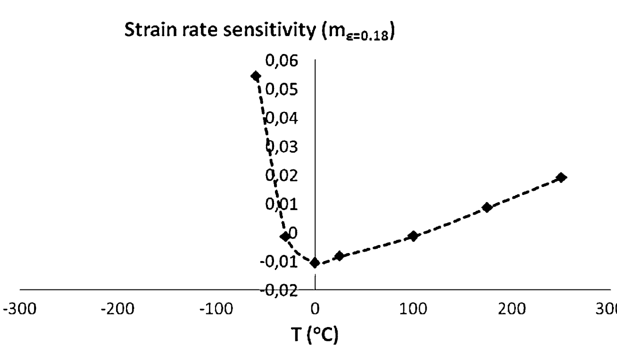

Fig. 4 Strain-rate sensitivity vs. temperature at ε = 0.18

increasing the true strain at −60 °C. Figure 3 illustrates that the strain-rate sensitivity is positive at 100, 175, and 250 °C. Although the data were generally scattered at 0, RT, and 100 °C, they were almost constant at 175. An increasing trend was seen at 250 °C. The influence of temperature on strain-rate sensitivity was also plotted at maximum load (ε = 0.18) as shown in Fig. 4. Figure 4 shows that the m value increases with increasing temperatures above 0 °C. However, it increases with decreasing temperatures below 0 °C. Total elongation (TE) and uniform elongation (UE) of the samples were determined to

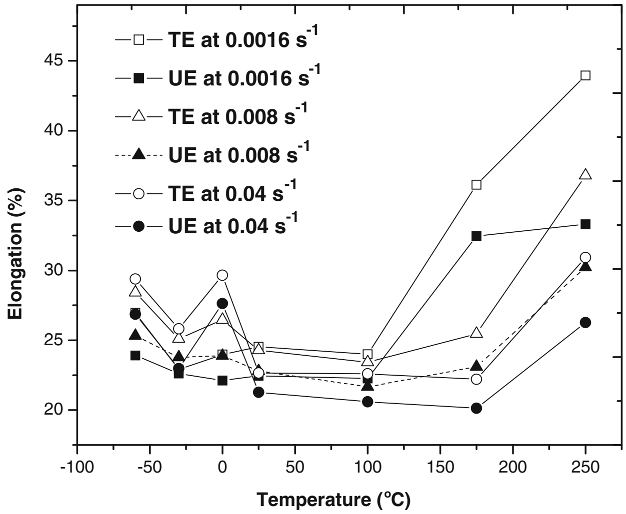

Fig. 5 Elongation vs. temperature at various strain rates

investigate the ductility of the material. The UE, which was investigated from deformation initiation to necking point, was also considered. The *m* value affects the length of the post-UE region where elongation goes after ultimate tensile strength (UTS), i.e., difference between total and UE. Figure 5 shows the variation between TE and UE with temperature for all testing temperatures and strain rates. In the negative temperature regions, the elongations were similar at 0 and −60 °C. In the positive temperature region, the trends of elongations were similar except for 175 °C. Different behaviors were observed between the UE and TE values at 175 °C and 0.0016 s^{-1}. Ductility of the material increased for the tests performed at elevated temperatures, especially at 175 and 250 °C. It was seen that the interval between TE and UE was more extended. The increase in the UEs can be correlated with dynamic recovering ability of the material at warm temperatures (Ref 29). The post-UE of the material was increased with temperature and decreased with strain rates.

As it is known, the strain-rate sensitivity values depend on the strain rates at which the test is performed. The similar finding was also observed by Halim et al. (Ref 10). Test results show that when *m* value is small (close to zero) or negative, ductility decreases. At colder temperatures, the ductility increases because the *m* value increases and it becomes positive. When the *m* value becomes negative, it is easy to notice appearance of the PLC localization bands on the material surface.

The value of *m* affects the point of necking initiation. Under the test conditions, when the material has negative *m* values, the fracture point is closer to the neck initiation point. If the *m* value is positive, the incipient neck location strengthens due to the fact that the local deformation speed increases, which forces the deformation to take place elsewhere (Ref 7). Test results show that the best formability conditions can be obtained when temperature is highest and strain rate is lowest. It is seen that strain-rate sensitivity is close to zero at 250 °C where the best formability for this alloy was observed in range of temperatures considered in this study. From the scientific viewpoint, there is still a lack of understanding of the interactions of different factors in controlling the *m* value, strain hardening, grain boundary sliding, cavitations, etc. (Ref 30). The *m* value cannot characterize microstructural processes in a local volume of the material because it is related to strain macrolocalization and is a macrocharasteristic of the material (Ref 31, 32).

4. Conclusion

Uniaxial tests were performed with AA 5754-O alloy in order to investigate the ductility and strain-rate sensitivity in the temperature range −60 to 250 °C and in the strain rate range from 0.0016 to 0.04 s^{-1}. The following conclusions were made:

- When *m* value is close to zero or negative, ductility of the alloy decreases. At colder temperatures, the ductility increased because the *m* value increased and becomes positive.
- It is observed that the strain-rate sensitivity measurement depended on the interval of chosen strain rates.
- The *m* value affects the point of neck initiation.
- When the material has a negative *m* value, the fracture point is closer to necking initiation point.
- At negative temperatures region, the deformation speeds have great effect on the formation of the PLC.

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