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An Investigation of Serrated Yielding and TEM Images in Series Aluminum Alloys

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Abstract—**Many Dynamic Strain Aging (DSA) tests are made on samples during tensile testing, but less during compression testing. Therefore, in this study is reasearched serrated yealding on aluminum samples subjected to compression. Compression tests were performed with help of servo controlled Schenck–Hydraulic PSB machine, which automatically generates force–height reduction graph at four different strain rates and four different temperatures. Emergence critical strain, disappearance strain and participation of discontinuities that occur during DSA is dependent on temperature, speed and chemical composition of aluminum alloys with different concentrations of magnesium and other elements. The analyses of TEM images have shown the impact of degree of deformation, deformation speed and temperature on investigated samples.**

Keywords—Aluminum alloys, serrated yielding, dynamic strain aging, strain rate.

I. INTRODUCTION

The reaction between dissolved Mg atoms and dislocations in Al-Mg alloy can be significantly accelerated by deflection of the solid solution at higher temperatures with increase the coefficient of diffusion of dissolved atoms, because of the process of deformation of education and many vacancies. Concomitant application of deformation and aging is called dynamic deformation aging. The dynamic range in deformation aging not only dissolved atoms, but also dislocates them. Dissolved atoms are moving towards the dislocation, but the formation of the atmosphere that would block dislocations equals the speed of the dissolved atoms with the rate of dislocation.

Blocking and releasing dislocation (substitution in solid solution) or forming new dislocation (in interstitial solid solution) occurs intermittently. The curve of deformation during tensile or compression test (as is the case in this paper), is shown as occurrence of discontinuous failure. Deformation curve is obtained with the characteristic form of discontinuities that occur intermittently.

Serrated yielding, also known as Portevin-Le Chatelier (PLC) effect, has been under intensive study for the past few decades. Until now, few models have given an explanation for different phenomena related to it. The two main branches of models are the dislocation-solute atom interaction models [1-4] and dislocation-precipitate interaction models [3]. In the first models, researchers disagree at what point dynamic strain ageing (DSA) occurs.

Dynamic strain ageing is thought to be the underlying mechanism that causes the PLC effect. Solute atoms form atmospheres around the mobile dislocations and the dislocations then have to break away from the atmospheres and continue their motion. In one of the dislocation/solute atom interaction models [1], dynamic strain ageing is thought to occur when the bulk diffusion of solute atoms has acquired a speed high enough to drag the moving dislocations (through vacancies created during the deformation). In the other model [2, 4], the solute/dislocation interaction occurs mainly at the obstacles where dislocations are temporarily held. The solute atoms can then diffuse to these dislocations and cause atmospheres to form around them.

To continue deformation, the dislocations have to break away from these atmospheres and multiply. This leads to serrated yielding. The results in this research tend to favor the latter model. However, the results indicate that the obstacles arresting mobile dislocations are mainly grain boundaries, as the grain size increases the grain boundaries/the main source of obstacles decrease. Accordingly, the magnitude of serrations, the main measure of serrated yielding, decreases, which means dynamic strain ageing is not so intense. In addition, has been thought that Mg atoms lead to serrated yielding. This also has been confirmed in this study, where three commercial materials with different Mg concentrations have been used. According to this, the serration magnitude increases with increasing Mg content. At low test temperatures, when a large number of Mg atoms are precipitated out of solid solution, not only the magnitude of the serrations is decreased, but the serrated phenomenon is delayed.

Plastic deformations of polycrystalline materials are complex inhomogeneous processes characterized by avalanches in the motion of dislocations. These types of complex dynamical systems are usually characterized by a large number of interacting components whose aggregate activity is nonlinear. These components can be identified in terms of few extrinsic and intrinsic variables. Strain, strain rate, temperature, solute concentration and specimen geometry serve as the extrinsic variables, whereas band width and band velocity are two of the intrinsic governing factors for the dynamics of the deformation bands in the PLC effect. The collective modes associated with the propagation of the deformation bands reduce enormously the degrees of freedom of the deformation dynamics in the PLC regime.

In uniaxial loading many dilute interstitial and substitutional alloys exhibit repeated stress drops followed by periods of reloading, during tensile (compression) deformation in certain ranges of strain rate (speed of deformation) and temperature. This repeated yielding (also known as serrations or discontinuous yielding) of these alloys is referred to as the Portevin-Le Chatelier (PLC) effect. Effect is associated with the repeated generation and propagation of plastic deformation bands.

To the best of our knowledge, no attempt has been made to characterize the underlying statistical nature of the PLC effect. This paper presents comprehensive statistical study of the PLC effect and detects the nature of the statistical process in Al-Mg alloys.

II. EXPERIMENTAL

Many DSA test have been made with samples under tensile, but less with samples under compression testing. Therefore, in this research will be conducted DSA tests with compressed samples. Materials used in this experiment were rods of Al polycrystalline alloys and their chemical compositions (table 1). In order to visualize the effective dimensionality of the PLC effect and its variation with strain, uniaxial compression tests have been performed. Samples were obtained by cutting rods with high/diameter ratio smaller than 2 (h0/d0 <2).

Compression tests were performed with help of servo controlled Schenck-Hydraulic PSB machine, which automatically generates force–height reduction graph at four different strain rates (1.66×10^{-3}**,** 4.166×10^{-3}, 4.166×10^{-2} and $8.33\times10^{-2}s^{-1}$) and four different temperature**s** (22, 100, 150 and 200^{0}C). In this range of strain rate is possible to observe three types of serrations.

TABLE I. CHEMICAL COMPOSITION (WT.%) OF ALLOYS

Al alloys	**Components (wt%.)**							
	Si	***Fe***	***Cu***	***Mn***	***Mg***	***Cr***	***Zn***	***Pb***
AlMg3	0.4	0.4	0.1	0.5	2.8	0.3	0.2	/
AlMg5	0.4	0.5	0.1	0.5	5.3	0.2	0.2	/
AlMgSi0.5	0.55	0.35	0.3	0.5	0.6	0.3	0.2	/
AlCuMgPb	0.4	-	3.849	-	0.726	-	-	0.87

III. RESOULTS AND DISSCUSION

A. *Dynamic Strain Aging (DSA) analysis*

The Portevin-Le Chatelier (PLC) effect has been investigated during compression tests of Al-Mg alloys at the strain rate and temperature regime where different types of serrations simultaneously appear on the deformation curve. Occurrence of A, B, A+B and C types of serrated yielding were detected during compression tests on the load vs. height reduction curves in all examined Al-Mg alloys. The appearances of serrations as well as their share depend on strain rate, temperature and Mg concentration.

The appearance of serrated yielding for different alloys depends on the temperature and strain rate (speed of deformation). This paper describes when and which type of serrate yielding will appear, when samples are subjected to the influence of different parameters.

TABLE II. INFLUENCE OF DIFFERENT PARAMETERS ON THE TYPE OF SERRATED YIELDING

Al alloys	**Parameters**				
	T °C	Θ 1.66×10^{-3} $\mathbf{s^{-1}}$	Θ 4.166×10^{-3} $\mathbf{s^{-1}}$	Θ 4.166×10^{-2} $\mathbf{s^{-1}}$	Θ 8.33×10^{-2} $\mathbf{s^{-1}}$
AlMg3	22	-	C	A,B,C	A,B,C
	100	-	C	A,B,C	/
	150	-	C	A,B	/
	200	-	/	/	/
AlMg5	22	-	C	A,B,C	A,B,C
	100	-	C	A,B,C	/
	150	-	C	A,B,C	/
	200	-	C	/	/
AlMgSi0.5	22	-	A,C	A,B,C	A,B,C
	100	-	A,C	A,B,C	/
	150	-	A,C	A,B,C	/
	200	-	C	A,B,C	/
AlCuMgPb	22	A, B	A, B	/	/
	100	A, B	A, B	/	/
	150	A, B	/	/	/
	200	C	/	/	/

(-) Not tested
(/) Not serrated yielding

Table 2 indicates the types of serrations for different Al alloys as function of temperature and strain rate

Examples of graphs load *vs.* height reduction with illustrations of different PLC effects in AlMg3, AlMg5, AlMgSi0.5 and AlCuMgPb alloys, respectively are shown on figs. 1-7.

In AlMg3 and AlMg5 alloys with Mg atoms, C-type of serrated yielding occurs at smaller strain rates and temperatures of 22^{o}C, 100^{o}C and 150^{o}C. However, at higher strain rates C-type appears in combination with A, B and A+B types (see table 2). The appearance of C-type of serrated yielding under the general level of deformation curve means that smaller loads are needed to unblock Cottrell atmospheres. At that moment, decrease of load appears on the deformation curve since lower stress is needed to move the unblocked dislocations.

In AlMgSi0.5 alloy types A and A+B serrations appear at the beginning of plastic deformation, whereas type C generally appears at higher degree of deformation. According to McCormick [15], A, B and A+B types of serrations are so-called "locking", and type C “unlocking “serrations.

Only A and A+B at lower strain rates and temperatures of 22^{o}C, 100^{o}C, 150^{o}C may be seen in AlCuMgPb alloy (see table 2). These types of serrations are illustrated in fig. 1 and fig. 2.

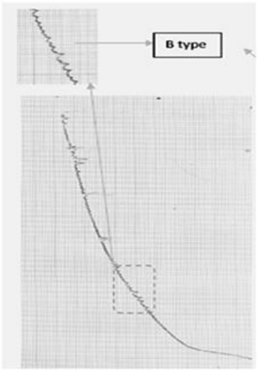

Fig. 1. Load vs. height reduction graph of AlCuMgPb

(T=22^{0}C, v=4,66x10^{-3} s^{-1})

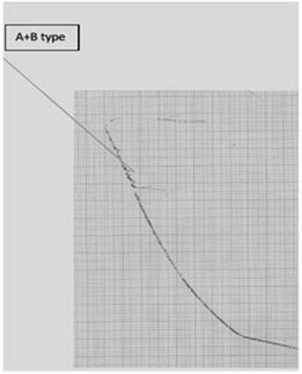

Fig . 2. Load vs. height reduction graph of AlCuMgPb

(T=100^{0}C, v=4,66x10^{-3} s^{-1})

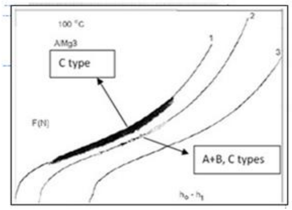

Fig. 3. Load vs. height reduction graph of AlMg3

(T=100^{0}C, 1=4,66x10^{-3} s^{-1},

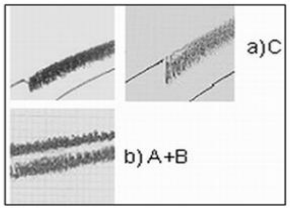

Fig. 4. Load vs. height reduction graph of AlMg3

a) C type b) A,B, C types

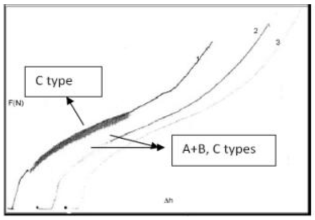

Fig. 5. Load vs. height reductiongraph of AlMg5 (T=1000C 1=4,66x10-3 s-1, 2=4,66x10-2 s-1, 3=8,33x10-3 s-1)

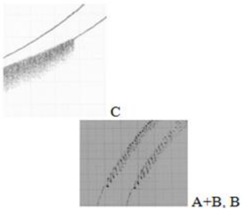

Fig. 6. Load vs. height reduction graph of AlMg5
a) C type b) A+B,B types

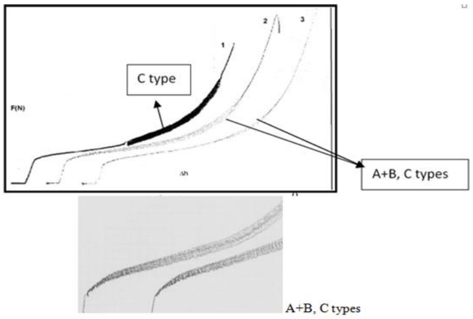

Fig. 7. Load vs. height reduction graph of AlMgSi0.5 (T= 22 ^{0}C 1=4,66x10^{-3} s^{-1}, 2=4,66x10^{-2} s^{-1}, 3=8, 33x10^{-3} s^{-1})

In contrast to type A of serrated yielding, occurrence of B-type serration is not considered to be due to formation of new deformation bands, but is believed to be the result of jerky propagation of such bands. Type B serrations occur when the fast-moving dislocations within the deformation band are affected by dynamic strain aging. When deformation band passes down the length it requires a significantly higher load to trigger a second deformation band than would be necessary under the normal work-hardening conditions, provided the aging time is sufficient for dislocations to get locked. All of these phenomena appear to support the theory that dynamic strain ageing occurs mainly at obstacles at which the moving dislocations are temporarily held. The Mg atoms then diffuse to these dislocations and cause them to be locked. The grain boundaries are formed by large numbers of dislocations and they are strong enough to block the mobile dislocations. There are also high-energy areas that can attract large numbers of Mg atoms.

When the mobile dislocations are held temporarily by the grain boundaries, Mg atoms can diffuse to them and form atmospheres. The smaller the grains, the greater the number of grain boundaries along the line of the mobile dislocations. This lead to greater number of dislocation tangles who are strong enough to hold the mobile dislocations long enough to let Mg atoms form atmospheres around them. Also, the greater number of dislocation tangles attracts more Mg atoms. These double effects make smaller grain samples which possess larger stress drops. When there is only one or two grains within the test sample, the grain boundaries are rarely barriers to the mobile dislocations. Mobile dislocations tend to move within one grain and there are no barriers that are as strong as the grain boundaries. Occasionally these mobile dislocations are held up by other obstacles, such as diffuse dislocation tangles or secondary precipitates, but they are not strong enough to hold the dislocations long enough to allow the Mg atoms to diffuse to them. In addition, Mg atoms tend to distribute more evenly within the grain and without other defects to assist their diffusion. Only very small number of these atoms moves to the dislocations. Thus, the dislocations break away from the Mg atoms much more easily and therefore the stress drop is very weak [8].

B. *Transmission Electron Microscopy(TEM) analysis*

How microstructures of pure Al, AlMg3 and AlMg5 samples, respectively, deform to different strains at room temperature is shown on fig. 8 to fig.11. These TEM micrographs demonstrate that the addition of Mg in Al-Mg alloys strongly influences the evolution of the dislocation structure during deformation.

On fig.8 a, b**,** c are given sub-structures of fallowing samples: pure Al, AlMg3 and AlMg5 alloys, where it is noted that dislocations are distributed evenly, forming dislocation non knit cells with small angle boundaries and mutual different orientation. The amounts of stages in the structure and particles on boundaries of the grains are significantly higher in AlMg5 alloy c) in comparison to the alloy AlMg3 b).

From fig. 9 and fig. 11 with degrees of reduction (22%, 40%, 60%, from AlMg3 and 10%, 50%, 70% from AlMg5) can be seen that dislocations form strips of a width of several hundred nm to 1μm. Inside the strips are less knit than those after bounds. Dislocations inside have uniform distribution. From the obtained images on fig.10 can be observed that in sample with higher temperature (c), dislocation density inside the strips is greater than sample with lower temperature (a), i.e. They are evenly distributed and begin to form the cells.

The sample with the lowest speed is similar in comparison to the sample with the greatest degree of deformation. This suggests that the large degree of deformation and low speed allows dislocations mutually to act and to form the sliding strips. Because of the low energy of packing defects of AlMg5, dislocations appear as straight lines as manifested in images, while of AlMg3 dislocations appear as interlocking i.e. as cell structure.

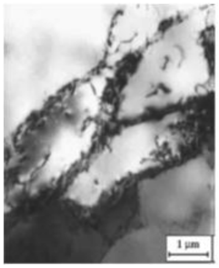

Fig.8a. Pure Al

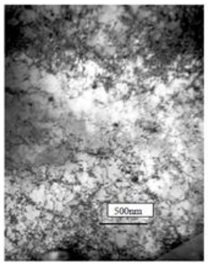

Fig. 8b. AlMg3

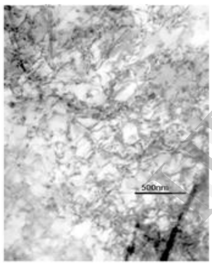

Fig.8c,. AlMg5

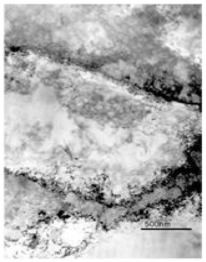

Fig.9a.AlMg3,4.166×1 $0^{-2}s^{-1}$,t=22^0C, ε=22%

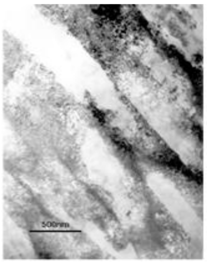

Fig.9b.AlMg3, 4.166×$10^{-2}s^{-1}$,t=22 ^{0}C,ε=50%

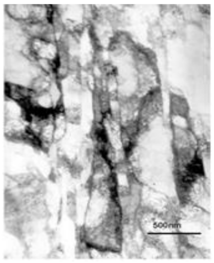

Fig.9c.AlMg3, 4.166×$10^{-2}s^{-1}$,t=22 ^{0}C,ε=70%

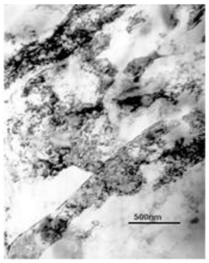

Fig.10a.AlMg3, 4.166×$10^{-3}s^{-1}$,t=22^0C, ε=70%

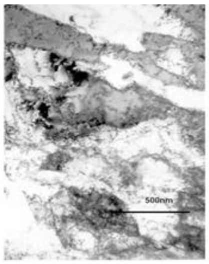

Fig.10b.AlMg3,8.3 3×$10^{-2}s^{-1}$,t=22^0C, ε=70%

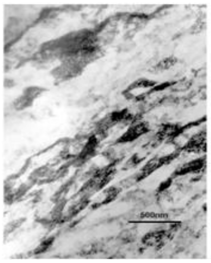

Fig.10c.AlMg3,4.166 ×$10^{-3}s^{-1}$,t=200^0C, ε=70%

IV. CONCLUSION

Occurrence of A, B, A+B and C types of serrated yielding was detected during compression tests on the load vs. height reduction curves in all examined Al-Mg alloys. The type C serrations are characterized by the load drop which is always below the general level of the stress-strain curve, in contrast to types A and B serrations which oscillate around the curve. B-type serrations usually occur at higher temperatures and higher strain rates than type C serrations (for AlMg3 and AlMg5) and often in combination with them at higher strain rates. B-type serrations usually occur at lower temperatures and lower strain rates than AlMgSi0.5 and AlCuMgPb serrations and often in combination with type A at higher strain rates. Type A serrations (for all alloys) are sometimes referred as locking serrations. They are observed when test conditions allow formation of solute atmospheres large enough to prevent unpinning. The load drop is the consequence of unblocking of previously pinned dislocations or the formation of new dislocations.

The serrations and microstructures developed during deformation in Al are strongly influenced by the interaction between the Mg solute atoms and the dislocations over a wide range of strains. The occurrence at (εc), disappearance (εk), type (A, B and C type) and participation of serrations that occur in DSA are dependent on temperature, strain rate and chemical composition of Al alloys. From the obtained experimental curves is determined that by increasing the temperature and strain rate at deformation has disappearance at the serrations.

The obtained experimental TEM images show that the major impact has the degree of deformation and strain rate of deformation. Low strain rate deformation is able to cause polygon processes, as well as the low level of deformation. High-speed deformation is similar to the large degree of deformation, as seen from the images. These structures can be recreated with smooth distribution of dislocation and smaller distances between dislocation i.e. high dislocation density.

The experimental tests performed in this paper have demonstrated the impact of Mg in the process of strengthening the appearance of discontinuities (serrations) during compression tests. However, little attention is dedicated to other elements in Al-Mg alloys, such as Si, Cu and Pb on explanation and determination of their mechanisms of action. Therefore, in the future it is necessary to be performed more different tests.

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