Hot deformation behaviour of Thixocast A356 aluminum alloy during compression at elevated temperature

M. Haghshenas, A. Zarei-Hanzaki, S.M. Fatemi-Varzaneh, H. Abedi

School of Metallurgical Engineering, University of Tehtran, Tehran, IRAN

ABSTRACT: In present study, the flow behaviour and constitutive equation of Thixocast A356 Al alloy has been studied using hot compression test at 450°C, 500°C, 540°C under the strain rates of 0.0001 sec^{-1}, 0.0005 sec^{-1}, 0.001 sec^{-1}, 0.01 sec^{-1}. The compression flow curves exhibited an initial sharp increase with strain followed by a moderate work-hardening behaviour. The maximum stress was decreased as the strain rate reduced and the temperature increased. At the lowest examined temperature (450°C) and the highest applied strain rate (0.01 sec^{-1}), a flow softening behaviour was observed. This was attributed to the morphological changes of the present precipitates.

Key words: Thixocast A356, hot deformation, dynamic recovery, constitutive equations.

1 INTRODUCTION

The extensive use of Thixocast aluminium alloys, belonging to the Al-Si system, is related to the possibility of producing defect free components in terms of void formation during casting operation [1]. As is well established the mechanical properties of A356 aluminium alloys in the Thixocast condition are higher than that of traditional casting ones [1]. This technological alloy is highly valued in aerospace and automotive industries [2].

As is well established, applying any deformation during heat treatment (i.e., thermo-mechanical treatment) are basically conducted to obtain the required structure and mechanical properties in both supersaturated and aged conditions of heat treatable A356 alloys. In any predetermined TMP cycle, the desired structure is obtained through controlling the related factors and phenomena such as deformation parameters, restoration processes, precipitation growth, etc [3].

The previous studies on hot workability of Al alloys [4-7] demonstrated that the high temperature deformation in these materials is controlled by dynamic recovery (DRV). This in fact is the characteristic feature of high stacking fault energy materials. The DRV is usually occurred at temperatures by which the dislocations have enough mobility and the rate of dislocation removal is equal to their production. Such a process may completely balance the effects of work hardening.

In the present study, the hot flow behaviour of a semi-solid thixocasted A356 alloy at different temperatures and strain rates has been investigated. Furthermore the related constitutive equations were also considered.

2 EXPERIMENTAL PROCEDURE

A semi-solid thixocasted A356 alloy has been examined in this study. The chemical composition of the alloy has been given in Table I.

Table I: The chemical composition of the experimental alloy

Wt(%)	Si	Mg	Fe	Cu	Mn	Ti	Zn	Sr
-	7.50	0.40	0.15	0.03	0.03	0.2	0.05	0.05

The hot compression test scheme was utilized to apply the predetermined thermo-mechanical treatment cycle. The compression specimens were machined in cylindrical shape with height to diameter ratio of 1.5 and the height of 11 mm. As is schematically shown in Fig. 1, thermo-mechanical treatment was performed to the final strain of 0.6 with different strain rates (0.0001 sec^{-1}, 0.0005 sec^{-1}, 0.001 sec^{-1}, and 0.01 sec^{-1}) at 450°C, 500°C, and 540°C. The high temperature, tests were conducted through a controllable resistance furnace adapted on an INSTRON 4820 universal testing machine. Each specimen was kept for 10 min. at the desired temperature to be homogenized. The Mica sheets were used to reduce the friction at the specimen-ends/die interface. The specimens were finally water quenched with maximum of 2 seconds delay.

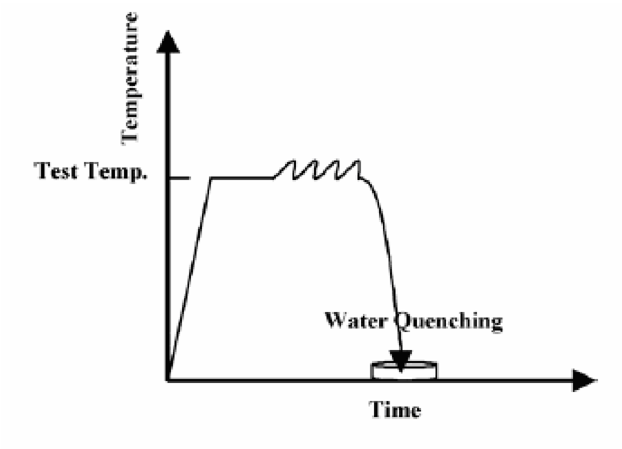

Fig 1. The schematic representation of the applied thermo-mechanical cycle

3 RESULTS AND DISCUSSION

3.1 Flow Behavior

The typical true stress-true strain curves are shown in Figs. 2-to-4. The observed behaviour in has been related to the occurrence of dynamic recovery. As is seen, the maximum stress increases with increasing the strain rate and decreasing the deformation temperature. The maximum stress is followed by steady state flow behaviour. Estey [2] has reported the flow behaviour of A356 alloys at temperatures higher than 500°C (e.g. 540°C). The related variation was attributed to the pinning of dislocation by solute drag effects. In fact, 540°C is a proper solutionizing temperature for A356 alloy and all the present precipitates are solutionized in Al matrix. This assists pinning the dislocation thereby resulting in work hardening the alloy. However the rate of work hardening is offsetting due to the work softening effects of occurring dynamic recovery. Decreasing the stress level by reducing the strain rates is related to the greater amount of dynamic recovery phenomenon during strain application.

As is seen at the lowest deformation temperature (450°C) and the highest strain rate (0.01 sec^{-1}), the work hardening is unable to level the work softening off. The latter results in a continuous softening thereby decreasing the flow stress by strain. Flow softening is a common characteristic of true stress-true strain curves of many alloys deformed at elevated temperatures. This may be caused by the deformation adiabatic heating and/or any microstructural instability such as dynamic recovery, texture formation, dynamic precipitation and dissolution [8].

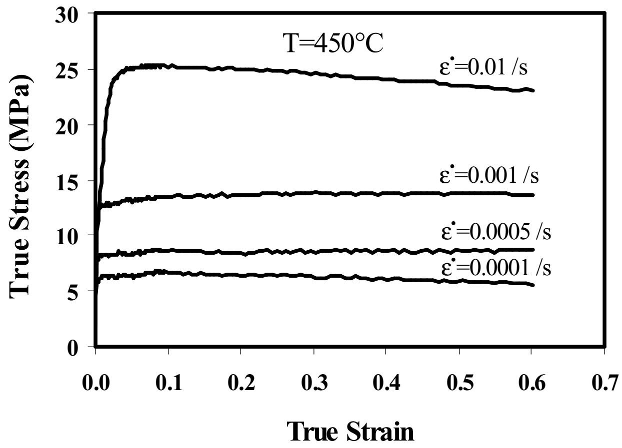

Fig. 2. The true stress-true strain curves at 450°C

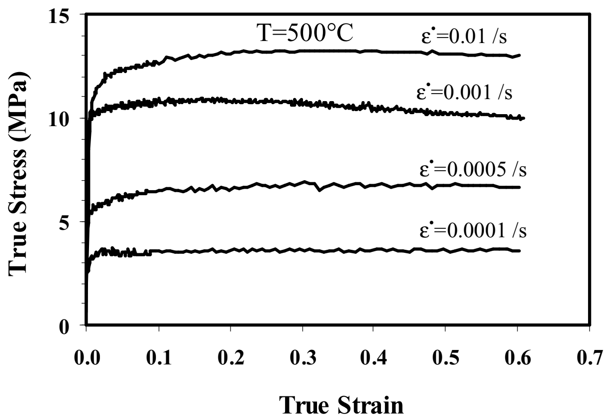

Fig. 3. The true stress-true strain curves at 500°C

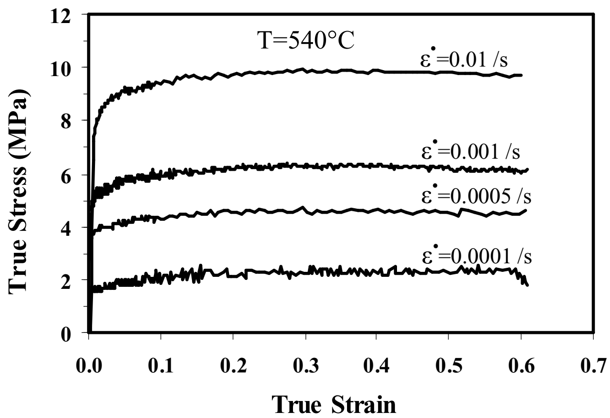

Fig. 4. The true stress-true strain curves at 540°C

Cerri [9, 10] and Blaz [11] believed that the dynamic recovery and coarsening of Mg/Si precipitates along with local flow near the boundaries are responsible for softening at high temperature. However by deformation at 450°C with strain rate of 0.01 sec^{-1}, the temperature and time by themselves appear to be inadequate for the nucleation of Mg/Si precipitates. This may be compensated through stimulating the transformation by applying the deformation. This may lead to a dynamic precipitation followed by increasing the flow stress. In this situation, the formation of solute-atmosphere hinders dislocation glides, raising the flow stress, but the fine precipitates are more effective source of strengthening. By continuing the deformation, due to the presence of such fine precipitates, the dislocation density increases, so pipe diffusion increases the kinetics of precipitates coarsening. The latter may increase the kinetics of recovery. So the decrease in flow stress beyond the maximum stress under this condition (450°C and 0.01 sec^{-1}) is related to the dynamic coarsening and morphological changes of Mg/Si precipitates from rode like (semi-coherent) to planar like (non-coherent).

In the other conditions, due to the higher temperature and/or longer time, the atomic diffusion increases and the precipitates nuclei before applying the deformation. This may lead to a significant decrease in the rate of work softening comparing to the aforementioned condition, due to the larger size of the precipitates [12]. As is well established, above the temperature range of morphological changes in precipitates (i.e., 300°C to 460°C) [13] the work hardening-work softening balance is achieved.

Figure 5 shows the variation of maximum stress as a function of temperature at deferent strain rates. This clearly indicates that the strengthening effect of particle-dislocation interaction gradually decreases with increasing temperature. This in turn, is easily explained by coarsening and, at higher temperature, dissolution of precipitates.

3.2 Constitutive Equations

In hot working processes, several constitutive equations have commonly been applied [8]:

$$\varepsilon^{\bullet} = A'\sigma^{n'} \exp(-\frac{Q_{HW}}{RT}) \quad (1)$$

$$\varepsilon^{\bullet} = A'' \exp(\beta\sigma) \exp(-\frac{Q_{HW}}{RT}) \quad (2)$$

$$\varepsilon^{\bullet} = A''(\sinh \alpha\sigma)^{n} \exp(-\frac{Q_{HW}}{RT}) \quad (3)$$

$$Z = \varepsilon^{\bullet} \exp(\frac{Q_{HW}}{RT}) \quad (4)$$

where A, A', A'', n', n, α and β are constants, Q_{HW} is the activation energy of high-temperature deformation, R is the gas constant, T is temperature and Z is the Zener-Hollomon parameter.

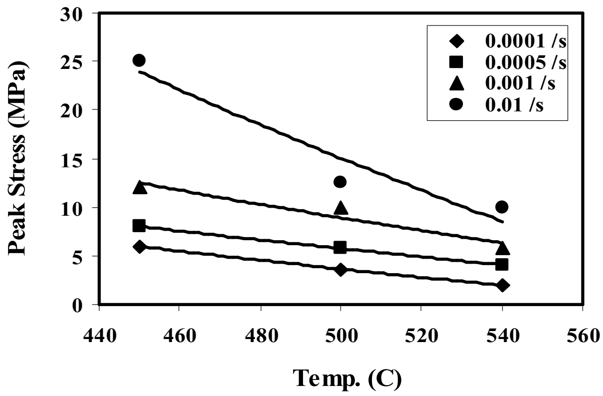

Fig. 5. The variation of maximum stress as a function of temperature

The power law, Eq. (1), and the exponential law, Eq. (2), break at a high stress and at a low stress, respectively. The hyperbolic Sin law, Eq. (3), is a more general one suitable for a wider range of stresses. For the alloys tested in stable conditions, Eq. (1) results in Q_{HW} values close to the activation energy of self-diffusion (Q_d) in Al [4]. Indeed, after slow cooling or overaging, due to the coarser particle size and larger spacing, the precipitates have a minor strengthening effect. In addition the solute level is also low in this condition. By contrast, where the alloy is examined in solution treated condition, very high values of the activation energy and of the stress exponent (even approaching infinity or negative values [4]) can be observed.

Figures 6 and 7 represent the Log (sinh $\alpha\sigma_P$) vs Log ($\varepsilon^{\bullet}$), and Log (sinh $\alpha\sigma_P$) vs 1000/T obtained from the true stress-true strain curves. The activation energy of hot working (Q_{HW}) is obtained from Eq. 5:

$$Q_{HW} = 2.3\ nRS \quad (5)$$

where n, S are the slopes of Log (sinh $\alpha\sigma_P$) vs Log ($\varepsilon^{\bullet}$) and Log (sinh $\alpha\sigma_P$) vs. 1000/T, respectively. It should be noted that α must be chosen in a way that lines in Fig. 7 would be parallel (α=0.08). The same analysis was repeated using α values ranging from 0.01 to 0.08 MPa^{-1} [4]. According to the diagrams in temperature range of 450°C to 540°C, activation energy is obtained to be 154kj/mol. This value is close to the "self diffusion" activation energy of pure aluminum (Q_L=143.4 kj/mol) [14].

In present study, the recovery is the controlling mechanism due to the precipitates coarsening, and removal of solute elements from the matrix. The calculated activation energy ($Q_L=Q_{HW}$) also confirms the activity of this mechanism.

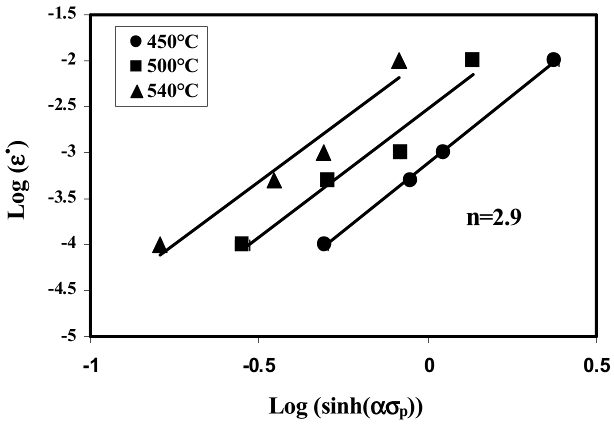

Fig. 6. The variation of strain rate with maximum stress (α=0.08)

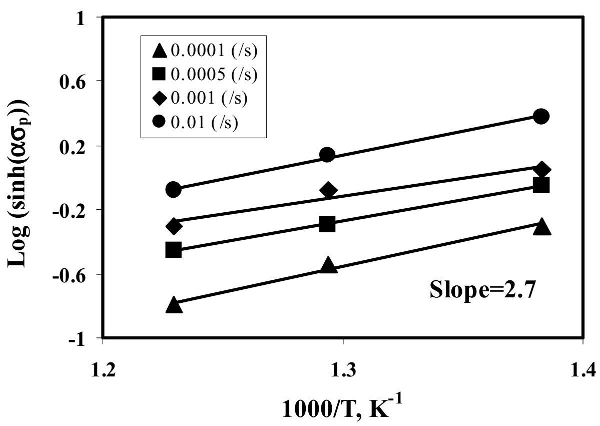

Fig. 7. The variation of maximum stress with temperature (α=0.08)

4 CONCLUSIONS

- A work softening behaviour is observed at 450°C and maximum applied strain rate (0.01 /s).
- At temperature higher than 500°C the deformation behaviour of the alloy is controlled by solute drag effects. The work hardening is minimal and flow stress becomes stable.
- The dynamic recovery is the deformation controlling mechanism. This was concluded form the fact that the other strengthening mechanism is being inactive (i.e. the precipitates coarsen and the solute elements coming out of the matrix.

REFERENCES

1. P. Cavaliere, E. Cerri, P. Leo, "Effect of heat treatment on mechanical properties and damage evolution of thixoformed aluminum alloys", Materials Characterization 55 (2005), pp. 35-42.
2. C.M. Estey, S.L. Cockcroft, D.M. Maijer, C. Hermesmann," Constitutive Behavior of A356 during the Quenching Operation", Materials Science and Engineering A383, 2004, pp. 245-251.
3. H.J. McQueen, "Micro-mechanisms of dynamic Softening dynamic softening in aluminium alloys during hot working", The Symposium Hot deformation of Aluminium, Detroit, 1991, pp.21-31.
4. S. Spigarelli, E. Evangelista, H.J. McQueen, "Study of hot workability of a heat treated AA6082 aluminum alloy", Scripta Materialia 49, 2003, pp. 179-183.
5. H.J. McQueen, W. Blum, "Dynamic recovery: sufficient mechanism in the hot deformation of Al (<99.99)", Mat. Sci. Eng. A, Vol. A290, 2000, pp. 95 - 107.
6. H. Yamagata, "Dynamic recrystallization and dynamic recovery in pure Aluminum at 583k", Acta Mat., Vol. 43(2), 1995, pp. 723 – 729.
7. B. Verlinden, P. Wouters, and H.J. McQueen, "Effect of different homogenization treatments on the hot workability of aluminum alloys", Material Science and Engineering A, Vol. 23, 1990, pp. 229 - 237.
8. Hui Zhang, Luoxing Li, Deng Yuan, Dashu Peng, "Hot deformation behavior of the new Al-Mg-Si-Cu aluminum alloy during compression at elevated temperatures, Materials Characterization, Volume 58, Issue 2, February 2007, Pages 168-173
9. E. Cerri, E. Evangelista and N. Ryum, "The relationship between microstructural and plastic instability in Al-4.0 wt pct Cu alloy", Met. Trans. A, Vol. 27A (10), 1996, pp. 2916 - 2922.
10. E. Cerri, E. Evangelista, A. Forcellese, and H.J. McQueen, "Comparative hot workability of 7012 and 7075 alloys after different pretreatments," Mat. Sci. Eng., Vol.A197, 1995, pp.181-198.
11. L. Blaz, E. Evangelista and M. Niewczas, "Precipitation effects during hot deformation of a Copper alloy", Met. Trans. A, Vol. 25A, 1994, pp. 257 - 266.
12. H. Shi, "Precipitate and Microstructure Development in Al-2014 Alloy During Heat Treatment and Hot

Deformation", in "Light Metals Processing and Applications", Canada, 1993, pp. 555-570.

13. J.Van De Langkruis, W.H. Kool, C.M Sellars, M.R. Van Der Winden and S. Van Der Zwaag "The effect of β, β' and β'' precipitates in a homogenised AA6063 alloy on the hot deformability and the peak hardness" Material Science and Engineering A, 2001, pp. 105-115.
14. F. Bardi, M. Cabibbo, E. Evangelista, S. Spigarelli, "An analysis of hot deformation of an Al-Cu-Mg alloy produced by powder metallurgy", Material Science and Engineering A, Vol. 339, 2003, pp. 43-52.