HOT DEFORMATION OF 6XXX SERIES ALUMINIUM ALLOYS

WYSOKOTEMPERATUROWE ODSZTAŁCENIE STOPÓW ALUMINIUM GRUPY 6XXX

The hot deformation behavior of the 6xxx aluminium alloys was investigated by compression tests in the temperature range 100°C-375°C and strain rate range 10^{-4}s^{-1} and 4x10^{-4}s^{-1} using dilatometer DIL 805 BÄHR Thermoanalyse equipped with accessory attachment deformation allows the process to execute thermo- plastic in vacuum and inert gas atmosphere. Associated microstructural changes of characteristic states of examined alloys were studied by using the transmission electron microscope (TEM). The results show that the stress level decreases with increasing deformation temperature and deformation rate. And was also found that the activation energy Q strongly depends on both, the temperature and rate of deformation. The results of TEM observation showing that the dynamic flow softening is mainly as the result of dynamic recovery and recrystallization of 6xxx aluminium alloys.

Keywords: Aluminum alloy, Hot deformation, Microstructural evolution, Activation energy

1. Introduction

In the last decade the hot workability process of aluminum and its alloys has been of both technical and scientific interest [1-6]. The 6xxx-series aluminium alloys contains magnesium and silicon as major alloying elements [6-12]. These multiphase alloys belong to the group of commercial aluminum alloys, in which relative volume; chemical composition and morphology of structural constituents exert significant influence on their useful properties [1,6-11]. Al-Mg-Si alloys that combine good strength, extrudability, favorable corrosion resistance with low cost have recently been used for automotive body sheet panel for weight saving, furniture, architectural facing and structures and transport vehicle frames. However, this is somewhat limited by reduced formability in these alloys, nevertheless both stiffness and mechanical properties are sufficiently high. High stacking fault energy alloys, such as aluminium alloys, undergo continuous dynamic recrystallization rather than discontinuous dynamic recrystallization during high temperature deformation. In particular, due to the high efficiency of dynamic recovery, new grains are not formed by a classical nucleation mechanism; high angle grains are formed by converting subgrain structures within the deformed original grains [5,6].

2. Material and experimental

The investigation has been carried out on the commercial aluminum alloy - appointed in accordance with the standard PN - EN 573-3; 6005, 6061, 6063 and 6082. The chemical composition of the alloys is indicated in Table 1.

| Alloy | Si  | Mg  | Mn  | Cu  | Fe  | Zn  | Ni  | Cr  | Ti  |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 6061  | 0.78| 1.07| 0.15| 0.35| 0.16| 0.042| 0.007| 0.35| 0.029|
| 6063  | 0.55| 0.55| 0.07| 0.026| 0.18| 0.02| 0.005| -   | 0.018|
| 6082  | 1.0 | 0.76| 0.56| 0.022| 0.16| 0.013| 0.004| -   | 0.023|
| 6005  | 0.77| 0.56| 0.12| 0.038| 0.20| 0.030| 0.008| 0.03| 0.02 |

In order to investigate the hot deformation behaviour of aluminium alloys 6xxx series under controlled conditions se-
The value of activation energy can be also estimated by applying following formula:

$$Q = \frac{\partial \ln \sigma}{\partial T^{-1}} \bigg|_\varepsilon$$

(6)

For the evaluation of coefficients required for determination of activation energy for alloys: 6005, 6061, 6063 and 6082, data obtained from deformation process within the range of 100-375°C, where plastic flow was stable, has been applied.

Microstructures of characteristic states of the examined alloys were observed using the transmission electron microscopes (TEM) Tesla BS-540 and Jeol-2100 operated at 120, 180 and 200kV. The thin foils were prepared by the electrochemical polishing in: 260 ml CH3OH + 35 ml glycerol + 5 ml HClO4 using Tenupol-3.

3. Results and discussion

Plastic deformation process of 6005, 6061, 6063 and 6082 aluminium alloys were conducted in the temperature range 100-375°C and deformation rates: 10^{-4} and 4\times10^{-4} s^{-1}. The shape of deformation curves depends mainly on the temperature of plastic deformation (Fig. 1 and 2).

![Fig. 1. True stress-true strain curves for 6005 aluminium alloy – for deformation rate of: a) 10^{-4} s^{-1} and b) 4\times10^{-4} s^{-1}.](image-url)
rate (Fig. 1 and 2). Alloys, which are submitted to deformation process in the temperature of 100°C are characterized by highest stress values (e.g. $\sigma_{pl} = 379$MPa – 6061 alloy, $\sigma_{pl} = 279$MPa – 6082 alloy, Tab. 2). Increasing the value of deformation temperature results in reduction of flow stress value. Similar dependence was observed if the deformation rate increased (Fig. 1, 2 and Tab. 2).

The analysis of influence degree of temperature in the range of 100 – 375°C and deformation rate of 6005, 6061, 6063 and 6082 alloys, indicates that dynamic recovery and recrystallization are dominant processes in recovery of their microstructure. The microstructure of analysed alloys after plastic deformation $\varepsilon_{rz} = 0.2$ in the temperature of 100°C is characterized by high density of dislocations which form irregular tangles, separated with dislocation-free areas (Fig. 3a). The deformation growth results in combining of irregular dislocation tangles and creation of continuous walls surrounding areas with low dislocations density (dislocation cells). The increase of actual deformation up to a value of approx. $\varepsilon_{rz} = 0.8$ leads to the rise of dislocations density in cells walls. At the same time, size reduction of dislocation dislocations cells and the elongation process of cells in the direction of plastic flow were observed (Fig. 3b).

**TABLE 2**

Flow stress $\sigma_{pl}$ of 6xxx aluminium alloys submitted to deformation, depending on temperature and deformation rate

| Alloy | Deformation rate $\varepsilon_{rz}$, s$^{-1}$ | Deformation temperature, °C | Stress $\sigma_{pl}$, MPa |
|-------|----------------------------------|--------------------------|--------------------------|
|       | 10$^{-4}$                           | 100  200  300  375       |                          |
| 6005  | 10$^{-4}$ s$^{-1}$                  | 270  128  50  32         |                          |
|       | 4×10$^{-4}$ s$^{-1}$               | 280  130  60  45         |                          |
| 6061  | 10$^{-4}$ s$^{-1}$                  | 379  217  115  75        |                          |
|       | 4×10$^{-4}$ s$^{-1}$               | 369  225  125  75        |                          |
| 6063  | 10$^{-4}$ s$^{-1}$                  | 225  128  62  50         |                          |
|       | 4×10$^{-4}$ s$^{-1}$               | 234  164  68  56         |                          |
| 6082  | 10$^{-4}$ s$^{-1}$                  | 215  125  79  68         |                          |
|       | 4×10$^{-4}$ s$^{-1}$               | 279  155  90  75         |                          |
Increasing the temperature of plastic deformation leads to reduction of plastic deformation value $\sigma_{pl}$ for all analysed alloys (Fig. 4). It was determined that the stress value $\sigma_{pl}$ is higher for deformation rate of $4 \times 10^{-4}$ s$^{-1}$, independently from compression process temperature (Tab. 3, Fig. 5).

Lower values of flow stresses $\sigma_{pl}$ are a result of change in microstructure morphology of alloys submitted to deformation process (dynamic recovery processes). Simultaneously, the annihilation process of dislocations, their rearrangement and formation of ordered low-energy dislocation structures occur (Fig. 6).

Dynamic recovery process successfully counteracts the strain hardening. Increasing the plastic deformation temperature for alloys up to 350-375°C intensifies the dynamic recovery processes (Fig. 7). It results in reaching a given plastic flow for lower critical deformation - $\varepsilon_{rc}$ = 0.1-0.2 (Fig. 1 and 2). There was also observed a decrease of stress flow value $\sigma_{pl}$ (down to 50-70 MPa), for which a plastic flow occurs in case of all analysed alloys. The inclination angles of $\sigma_{pl}$–1/T curves for 6005 alloys are similar (Fig. 8). The linear dependency of stress for deformation temperature range of 100-175°C for both deformation rates $10^{-4}$ and $4 \times 10^{-4}$ s$^{-1}$, indicates that the stress $\sigma_{rc}$ = 0.8 does not allow reaching the range of a given plastic flow.

The dependency graphs $\ln \sigma_{pl} = f(1/T)$ and $\ln \sigma_{pl} = f(\ln \dot{\varepsilon})$ (Fig. 8and 9) were used as a basis for determining the values $\frac{\partial \ln \sigma_{pl}}{\partial 1/T}$ and $\frac{\partial \ln \sigma_{pl}}{\partial \ln \dot{\varepsilon}}$ in equation (3) and the values of activation energy of deformation process for 6xxx aluminium alloys. It was established that the activation energy Q strongly depends on both, the temperature and rate of deformation. Only in case of 6005 alloy, in the temperature range of 100-350°C no in-
fluence of deformation rate on activation energy was observed (Table 3).

![Graph](image)

**Fig. 9. Influence of deformation rate and temperature on the value of flow strain for 6005 aluminium alloy**

**TABLE 3**

The value of activation energy for 6xxx aluminium alloys submitted to deformation process in a temperature range of 100-375°C

| Alloy | Deformation rate \(\dot{\varepsilon}, \text{s}^{-1}\) | Temperature, °C | Activation energy \(Q, \text{kJ/mol}\) |
|-------|---------------------------------|----------------|----------------------------------|
| 6005  | \(10^{-4}\)                      | 100, 150, 175, 200, 250, 300, 350, 375 | 4x10^-4, 231.7, 169.7, 259.0, 155.8, 207.2, 110.4, 290.7 |
| 6061  | \(4x10^{-4}\)                    | 100, 150, 175, 200, 250, 300, 350, 375 | 53.6, 63.6, 54.5, 212.8, 194.8, 165.6, 152.8, 54.5 |
| 6063  | \(4x10^{-4}\)                    | 100, 150, 175, 200, 250, 300, 350, 375 | 64.8, 69.9, 58.4, 231.7, 249.8, 172.6, 207.1, 242.3 |
| 6082  | \(4x10^{-4}\)                    | 100, 150, 175, 200, 250, 300, 350, 375 | 79.9, 113.3, 124.8, 212.6, 212.6, 124.8, 212.6, 212.6 |

In the temperature range of 100-350°C, the average value of activation energy for deformation process of 6005 aluminium alloy is equal to 212.8 kJ/mol and in case of deformation process of pure aluminium performed in elevated temperature – 147 kJ/mol. The equations (1)-(6) and obtained experimental data were used as a basis for determining dependency \(\sigma_{pl} = f(\dot{\varepsilon}, T)\) (Fig. 1, 3, 8, 9). During calculations, the values for linear dependency between \(\ln \sigma_{pl}\) and \(1/T\) were taken into account:

- 6005 alloy: \(\dot{\varepsilon} = 3.26 \times 10^{12} \sinh (\alpha \sigma)^{1.71} \cdot \exp \left(\frac{-Q}{RT}\right)\)
- 6061 alloy: \(\dot{\varepsilon} = 8.37 \times 10^{13} \sinh (\alpha \sigma)^{2.98} \cdot \exp \left(\frac{-Q}{RT}\right)\)
- 6063 alloy: \(\dot{\varepsilon} = 8.58 \times 10^{13} \sinh (\alpha \sigma)^{3.02} \cdot \exp \left(\frac{-Q}{RT}\right)\)
- 6082 alloy: \(\dot{\varepsilon} = 7.68 \times 10^{13} \sinh (\alpha \sigma)^{2.79} \cdot \exp \left(\frac{-Q}{RT}\right)\)

The analysis of obtained results (Tab. 3) allows to state, that the activation energy \(Q\) of investigated alloys depends strongly on both, the temperature and rate of deformation.

**4. Summary**

The link between the hot deformation behaviour of aluminium alloys of the 6xxx series and the microstructural evolution occurring during deformation process is studied in order to improve the understanding and the control of the deformability of these alloys were investigated from a campaign of compression tests on dilatometer by varying the deformation temperature (range of 100°C-375°C) and the deformation rate: \(10^{-4}s^{-1}\) and \(4x10^{-4}s^{-1}\). The results of deformation process give clues about the difference in deformability between the examined alloys. It has been found that the level of stress was decreasing with the temperature ramp and value of true strain applied. The analysis of results showed that the level of activation energy depends strongly on either temperature and strain rate. TEM observations showed consequences of dynamic softening processes occurring in the microstructure of the materials, which involves formation of subgrains giving rise to an equiaxed structure of high-angle boundaries and nucleation-and-growth process. These results prove that in these alloys dynamic recovery and recrystallization process occurred.

On the basis of analysis of obtained results it was established that the activation energy of aluminium alloys deformation in elevated temperature range depends on phase composition, state of matrix and the strengthening phase content. For high temperature alloy characterized by a presence of stable phase constituents of microstructure, the value of activation energy of deformation is similar to activation energy of self-diffusion for aluminium. In metastable state (e.g. supersaturated, for further heat treatment) it is characterized by a significant increase of activation energy of deformation process. The value of activation energy \(Q\) for analysed 6061, 6063 and 6082 alloys in metastable-supersaturated state is clearly dependent on both, the temperature and rate of deformation.

**REFERENCES**

[1] H. Zhang, L. Li, D. Yuan, D. Peng, Mater Character **58**, 168-173 (2007).
[2] S.C. Bergsma, M.E. Kassner, X. Li, M.A. Wall, Mater Sci Eng, A Struct Mater:Prop Microstruct Process **254**, 112-8 (1998).
[3] S. Spigarelli, E. Evangelista, H.J. McQueen, Scr Mater, **49**, 179-83 (2003).
[4] H.J. McQueen, X. Xia, Y. Cui, B. Li, Q. Meng, Mater. Sci. Eng. **319-321** (2001).
[5] H.J. McQueen, N.D. Ryan, Mater. Sci. Eng. **322**, 43-63 (2002).
[6] Aluminium Handbook. vol.1 Fundamentals and materials. Aluminium-Verlag Marketing & Kommunikation GmbH, Düsseldorf 1999.
[7] F. King, Aluminium and its alloys. John Willey & Sons, New York-Chichester-Brisbane-Toronto, 1987.
[8] L.F. Mondolfo, Aluminium Alloys: Structure and Properties. Butterworths, London-Boston, 1976.
[9] M. Warmuzek, G. Mrówka, J. Sieniawski, J. Mater. Proc. Techno. \textbf{157-158}, 624-632 (2004).

[10] G. Mrówka-Nowotnik, J. Sieniawski, M. Wierzbińska, Arch. Mater. Sci. Eng. \textbf{28}, 69-76 (2007).

[11] G. Mrówka-Nowotnik, J. Sieniawski, M. Wierzbińska, J. Achiev. Mater. Manufac. Eng. \textbf{20}, 155-158 (2007).

[12] M. Warmuzek, J. Sieniawski, K. Wicher, G. Mrówka-Nowotnik, J. Mater. Proc. Techno \textbf{175}, 421-426 (2006).

[13] L. Błaż, Dynamiczne procesy strukturalne w metalach i stopach. Wydawnictwa AGH, Kraków 1998.

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