A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
Volume 60 2015 Issue 2
DOI: 10.1515/amm-2015-0263

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# HOT DEFORMATION OF 6XXX SERIES ALUMINIUM ALLOYS

# WYSOKOTEMPERATUROWE ODKSZTAŁCENIE STOPÓW ALUMINIUM GRUPY 6XXX

The hot deformation behavior of the 6xxx aluminum 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

Obróbkę cieplno-plastyczną stopów aluminium grupy 6xxx prowadzono w zakresie temperatury 100°C-375°C i prędkości odkształcania $10^{-4}s^{-1}$ i $4x10^{-4}s^{-1}$ na dylatometrze DIL 805 BÄHR Thermoanalyse wyposażonym w przystawkę odkształceniową umożliwiającą wykonanie procesu odkształcania w próżni i w atmosferze gazu obojętnego. Zmiany mikrostruktury badanych stopów, zachodzące w charakterystycznych stadiach obróbki cieplno-plastycznej, badano za pomocą transmisyjnego mikroskopu elektronowego (TEM). Ustalono, że wielkość naprężenia zmniejsza się wraz ze wzrostem temperatury i wielkości odkształcenia. Również energia aktywacji Q w dużym stopniu zależy zarówno od temperatury jak i prędkości odkształcania. Wyniki obserwacji mikrostruktury TEM wykazały, że dynamiczne mięknięcie materiałów jest głównie wynikiem zachodzących procesów zdrowienia dynamicznego i rekrystalizacji stopu aluminium 6xxx.

## 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.

TABLE 1
Chemical composition of the investigated alloys, %wt.

| 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-

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ries uniaxial, isothermal compression tests were conducted at different temperatures and two strain rates using dilatometer *DIL 805 BÄHR Thermanalyse* equipped with compression adapter allowing to carry out deformation tests under vacuum or partial argon/gas pressure. Precipitation occurrences during aging while the samples are to be compressed make the alloys suitable for studying the interaction of deformation and dynamic precipitation process. To intensify this phenomenon the solution treated alloys: 6005, 6061, 6063 and 6082 have been compressed at relatively low constant strain rates: $\dot{\varepsilon} = 10^{-4}$ and $4 \cdot 10^{-4}$ $s^{-1}$ within the temperature range (100-375°) corresponding to temperatures of precipitation of hardening phases up to the true strain of $\varepsilon = 0{,}8$. Compression tests were carried out for long enough time to allow diffusion to control processes developing when the alloys were deformed. Thus, solution heat-treated cylindrical samples $\varphi$5 mm×10 mm were conductive heated with the heat rate of 10°C/s to the temperature where compression test was initiated. After the test, the samples instantaneously were cooled down to room temperature with the rate of 50°C/s. The temperature was controlled by a type K thermocouple inserted and welded in the opening hollowed out in the central part of the sample. The opening ($\varphi$0,1 mm) was performer by spark erosion technique. A combination of graphite and molybdenum foils was used to reduce the friction between the anvils and the specimen as well as the gradient of temperature along the samples. The tests were carried out in an argon atmosphere.

The obtained results were used for evaluation of coefficients required for determination of Q value of the hot deformation process applied to aluminium alloys 6xxx series. For the range of deformation parameters employed, flow stress as a function of deformation temperature and strain rate was analyzed using hyperbolic-sine Arrhenius type equation [13]:

$$\dot{\varepsilon} = A\,[\sinh(\alpha\sigma)]^n \cdot \exp\left(\frac{-Q}{RT}\right) \tag{1}$$

where: $A, \alpha, n$ – material constants; $\dot{\varepsilon}$- effective strain rate $s^{-1}$; $Q$ – experimental activation energy for deformation process kJ/mol; $T$ – deformation temperature; °C, $\sigma$ – flow stress value ($\sigma_{pl}$), or stress corresponds to the first maximum at a true stress/true strain curve ($\sigma_{max}$), MPa; $R$ – universal gas constant (8,314 J/mol·K)
the equation (1) can be rearranged to the following form:

$$\ln\dot{\varepsilon} = \ln\left(A\,[\sinh(\alpha\sigma)^n]\right) - \frac{Q}{R}\cdot T^{-1} \tag{2}$$

then it can be modified as follows:

$$\left.\frac{\partial \ln\dot{\varepsilon}}{\partial T^{-1}}\right|_{\sigma} = -\frac{Q}{R} \tag{3}$$

This equation (3) allows to determine an activation energy for doeformation process carried out at $\sigma$ = const., eg.: in the creep test. For the process undergoes at constant strain rate the equation (3) can be rearranged to:

$$\left.\frac{\partial \ln\dot{\varepsilon}}{\partial T^{-1}}\right|_{\sigma} = -\left.\frac{-\partial \ln\dot{\varepsilon}}{\partial \ln[\sinh(\alpha\sigma)]}\right|_{T} \cdot \left.\frac{\partial \ln[\sinh(\alpha\sigma)]}{\partial T^{-1}}\right|_{\dot{\varepsilon}} = -\frac{Q}{R} \tag{4}$$

hence:

$$Q = R \cdot \left.\frac{\partial \ln\dot{\varepsilon}}{\partial \ln[\sinh(\alpha\sigma)]}\right|_{T} \cdot \left.\frac{\partial \ln[\sinh(\alpha\sigma)]}{\partial T^{-1}}\right|_{\dot{\varepsilon}} \tag{5}$$

The value of activation energy can be also estimated by applying following formula:

$$Q = \frac{\left.\frac{\partial \ln\sigma}{\partial T^{-1}}\right|_{\dot{\varepsilon}}}{\left.\frac{\partial \ln\sigma}{\partial \ln\dot{\varepsilon}}\right|_{T}} \tag{6}$$

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 $CH_3OH$ + 35 ml glycerol + 5 ml $HClO_4$ 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).

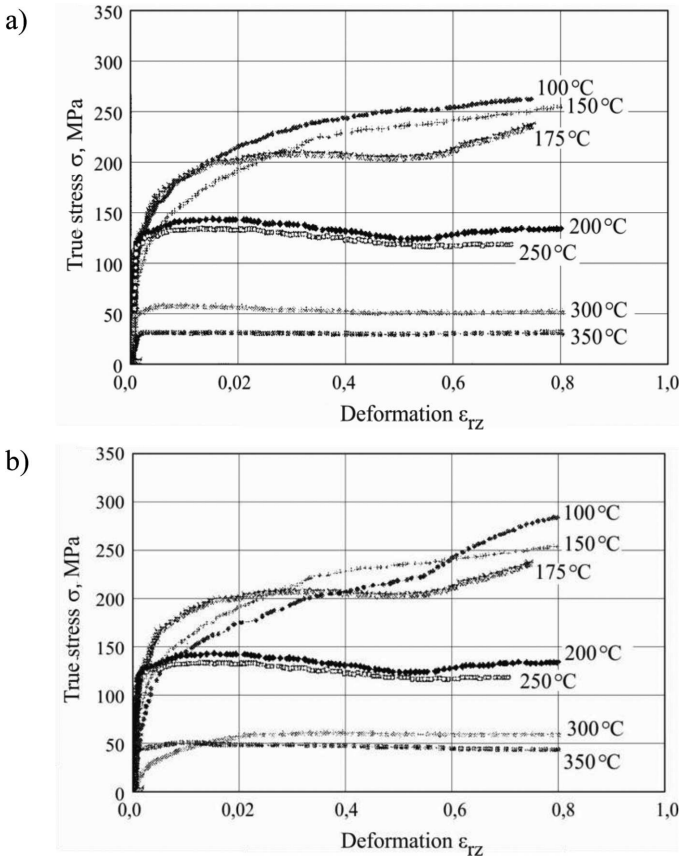


Fig. 1. True stress-true strain curves for 6005 aluminium alloy – for deformation rate of: a) $10^{-4}$ $s^{-1}$ and b) $4\times10^{-4}$ $s^{-1}$

The analysis of plastic deformation process during a compression test showed that the value of flow stress for 6xxx aluminium alloy depends on temperature and deformation

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. $\sigma_{pl}$ =379MPa – 6061 alloy, $\sigma_{pl}$ =279MPa – 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).

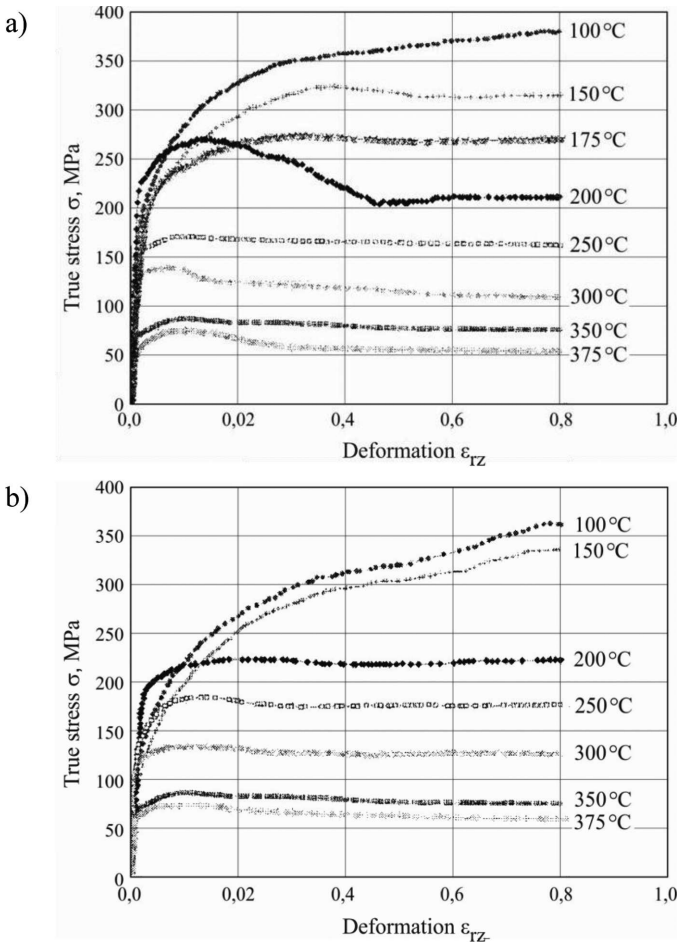


Fig. 2. True stress-true strain curves for 6061 aluminium alloy - for deformation rate of: a) $10^{-4}$ $s^{-1}$ and b) $4\times10^{-4}$ $s^{-1}$

TABLE 2

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

| Alloy | Deformation rate $\dot{\varepsilon}$, $s^{-1}$ | Deformation tepmperature, °C | | | |
|---|---|---|---|---|---|
| | | 100 | 200 | 300 | 375 |
| | | Stress $\sigma_{pl}$, MPa | | | |
| 6005 | $10^{-4}$ $s^{-1}$ | 270 | 128 | 50 | 32 |
| | $4x10^{-4}$ $s^{-1}$ | 280 | 130 | 60 | 45 |
| 6061 | $10^{-4}$ $s^{-1}$ | 379 | 217 | 115 | 75 |
| | $4x10^{-4}$ $s^{-1}$ | 369 | 225 | 125 | 75 |
| 6063 | $10^{-4}$ $s^{-1}$ | 225 | 128 | 62 | 50 |
| | $4x10^{-4}$ $s^{-1}$ | 234 | 164 | 68 | 56 |
| 6082 | $10^{-4}$ $s^{-1}$ | 215 | 125 | 79 | 68 |
| | $4x10^{-4}$ $s^{-1}$ | 279 | 155 | 90 | 75 |

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).

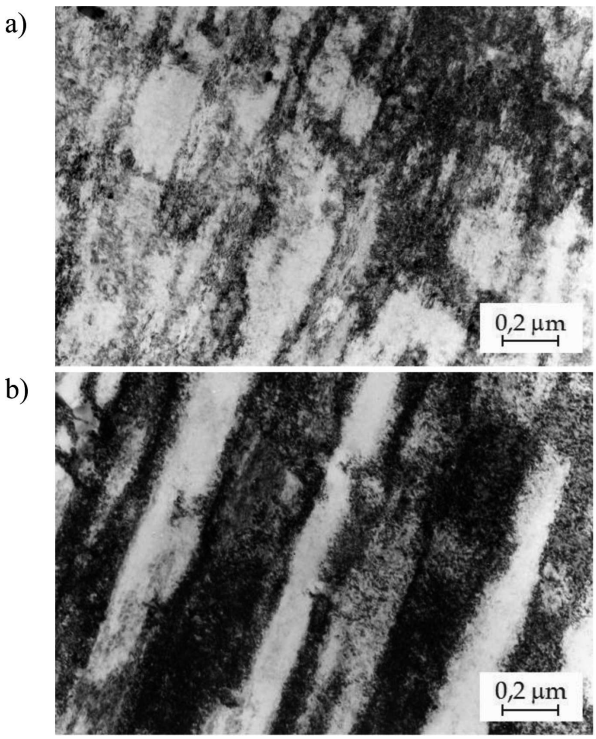


Fig. 3. The microstructure of 6061 aluminium alloy after plastic deformation in the temperature of 100°C

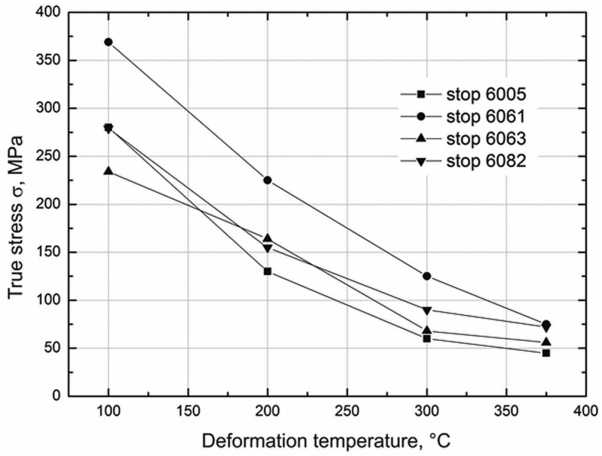


Fig. 4. The dependence of flow stress $\sigma_{pl}$ on deformation temperature for 6xxx aluminium alloys

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 $4\times10^{-4}$ $s^{-1}$, independently from compression process temperature (Tab. 3, Fig. 5).

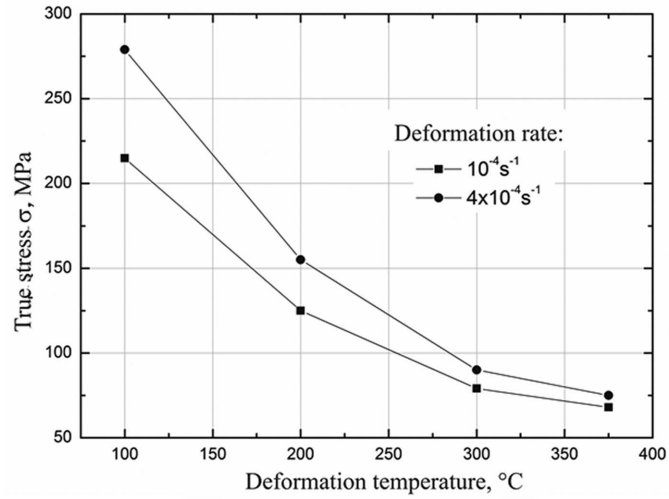


Fig. 5. The dependence of flow stress $\sigma_{pl}$ of 6082 alloy on temperature and deformation rate

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).

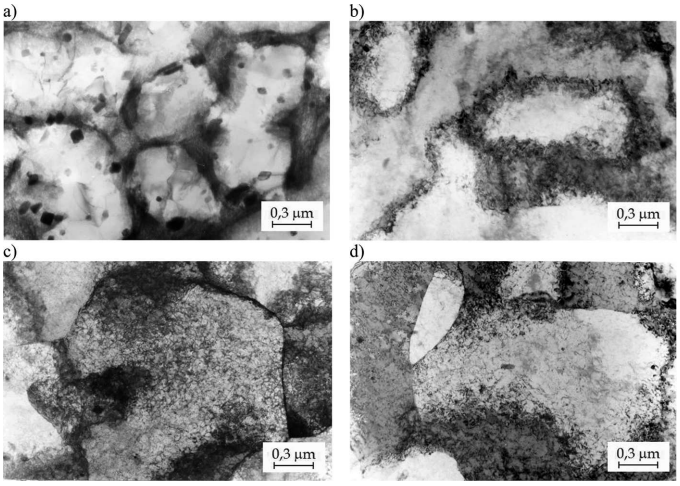


Fig. 6. The microstructure of 6063 alloy after plastic deformation in the temperature of: a,b) $T_\varepsilon$ – 200°C, $\dot{\varepsilon}$ = 0,001$s^{-1}$; c,d) $T_\varepsilon$ - 300°C, $\dot{\varepsilon}$ = 0,001$s^{-1}$

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 - $\varepsilon_{rz}$ =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 $4x10^{-4}$ $s^{-1}$, indicates that the stress $\varepsilon_{rz}$ = 0,8 does not allow reaching the range of a given plastic flow.

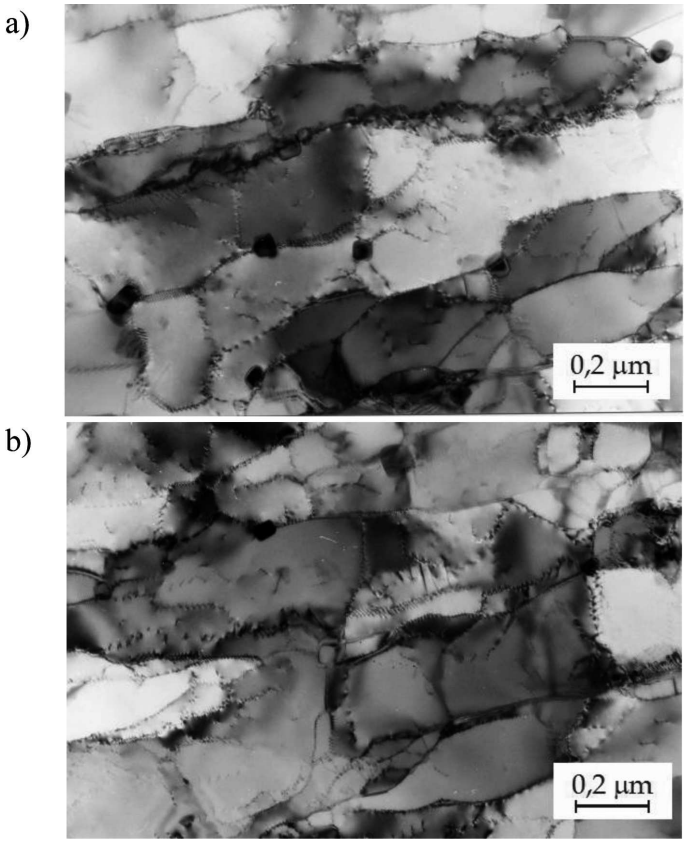


Fig. 7. The microstructure of 6063 alloy after plastic deformation $T_\varepsilon$ – 375°C, $\dot{\varepsilon}$ =0,001$s^{-1}$

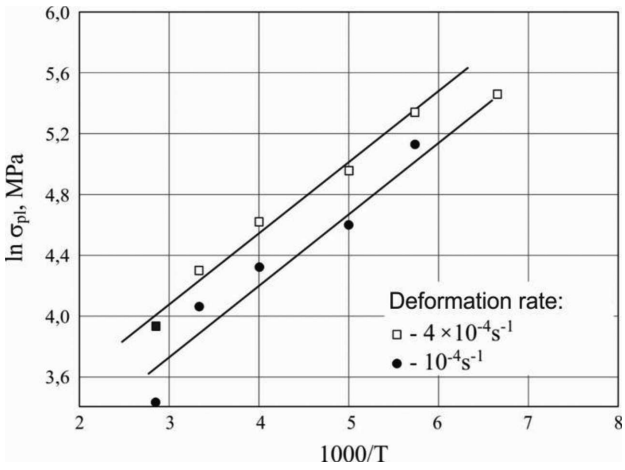


Fig. 8. The influence of temperature and deformation rate on the value of flow strain of 6005 aluminium alloy – linear extrapolation of experimental results in temperature range of 150-350°C

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 $\frac{\partial \ln \sigma}{\partial T^{-1}}\Big|_{\dot{\varepsilon}}$ and $\frac{\partial \ln \sigma}{\partial \ln \dot{\varepsilon}}\Big|_{T}$ 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).

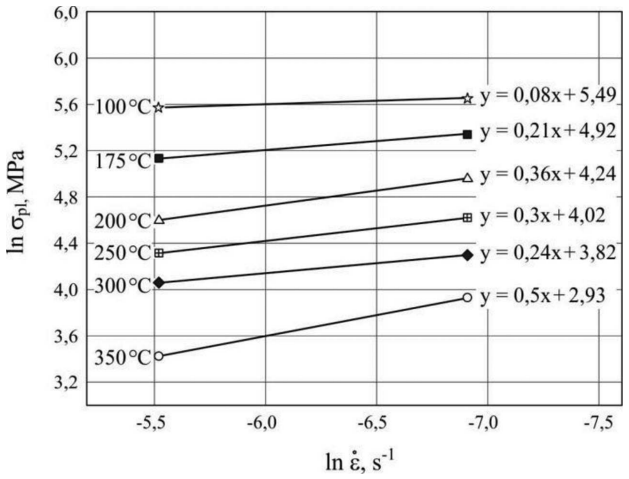


Fig. 9. Influence of deformation rate and temperature on the value of flow strain for 6005 aluminium alloy

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 $\dot{\varepsilon}$, $s^{-1}$ | Temperature, °C | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 100 | 150 | 175 | 200 | 250 | 300 | 350 | 375 |
| | | Activation energy Q, kJ/mol | | | | | | | |
| **6005** | $\mathbf{10^{-4}}$ | 96.9 | - | 169.6 | 193.8 | 242.3 | 290.7 | 283.9 | - |
| | $\mathbf{4x10^{-4}}$ | 96.9 | 145.4 | 169.7 | 193.9 | 242.3 | 290.8 | 339.2 | - |
| **6061** | $\mathbf{10^{-4}}$ | 55.2 | 82.8 | 96.6 | 110.4 | 138.0 | 165.64 | 193.3 | 207.1 |
| | $\mathbf{4x10^{-4}}$ | 69.1 | 103.6 | 120.9 | 138.2 | 172.7 | 207.2 | 241.8 | 259.0 |
| **6063** | $\mathbf{10^{-4}}$ | 50.7 | 77.0 | 90.9 | 102.8 | 123.6 | 141.6 | 183.4 | 169.2 |
| | $\mathbf{4x10^{-4}}$ | 63.6 | 96.2 | 113.3 | 124.8 | 150.0 | 179.6 | 220.1 | 215.7 |
| **6082** | $\mathbf{10^{-4}}$ | 53.6 | 79.9 | 94.6 | 115.8 | 133.9 | 155.8 | 191.2 | 214.4 |
| | $\mathbf{4x10^{-4}}$ | 64.8 | 99.6 | 112.7 | 126.2 | 152.4 | 199.2 | 231.7 | 249.8 |

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: $\dot{\varepsilon} = 3.26 \times 10^{12} [\sinh(\alpha\sigma)]^{1,71} \cdot \exp\left(\frac{-Q}{RT}\right)$ (7)
- 6061 alloy: $\dot{\varepsilon} = 8,37 \times 10^{13} [\sinh(\alpha\sigma)]^{2.98} \cdot \exp\left(\frac{-Q}{RT}\right)$ (8)
- 6063 alloy: $\dot{\varepsilon} = 8.58 \times 10^{13} [\sinh(\alpha\sigma)]^{3,02} \cdot \exp\left(\frac{-Q}{RT}\right)$ (9)
- 6082 alloy: $\dot{\varepsilon} = 7.68 \times 10^{13} [\sinh(\alpha\sigma)]^{2,79} \cdot \exp\left(\frac{-Q}{RT}\right)$ (10)

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 theses 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.

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*Received: 20 February 2014.*