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Original Article

Constitutive equation and microstructure evaluation of an extruded aluminum alloy

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ABSTRACT

The flow-stress behavior of an extruded aluminum alloy has been studied by conducting a set of warm and hot compression tests. The compression tests were carried out in the temperature range of 373 K–773 K and strain rates of 0.001, 0.01 and 0.1 s^{-1}, up to a strain of 0.5. Based on the results obtained from these tests, a mathematical model was obtained to predict flow stress for a given strain. The effect of temperature and strain rate on deformation behavior was ascertained by determining the Zener–Hollomon parameter. The influence of strain has been incorporated by employing an Arrhenius-type constitutive equation, considering the related material constants as functions of strain. The comparison of results indicated good agreement between the predicted and measured flow-stress values in the relevant temperature range. The correlation coefficient and average absolute relative error of the model were found to be 0.9965 and 4.26% respectively confirming good accuracy.

1. Introduction

Aerospace and automotive industries widely use aluminum alloys for manufacturing the structural components [1]. Comprehensive review of the research work carried out in the high temperature flow behavior of aluminum and its alloys can be found in [2]. Further investigation is required to understand the characteristics of certain aluminum alloys under different processing conditions and forming processes. Extrusion is inevitably used in automotive and structural applications as a preliminary process. The present work has thus been focused on arriving at a relationship between the flow stress, strain, strain rate and temperature to predict the flow behavior of extruded zinc based aluminum alloy. Toward this end, hot compression tests were conducted with a range of strain rates and temperatures. The experimental stress–strain data thus obtained had been employed to derive the constitutive equation relating flow stress, strain rate and temperature incorporating the proper compensation of strain. Finally, the validity of the developed constitutive equation has been examined for the processing conditions considered.

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Table 1 – Chemical composition (wt.%) of aluminum alloy.

Element	Zn	Mg	Cu	Fe	Si	Cr	Ni	Ti	Al
Measured (wt.%)	6.09	2.68	1.28	0.18	0.13	0.12	0.01	0.01	Bal

2. Experimental details

2.1. *Material*

The chemical composition of the commercial aluminum alloy used in this work is given in Table 1. The aluminum alloy has been produced by using a vortex method. The crucible was charged with 1200 g of aluminum alloy, and heated up to 650 °C for melting. The graphite stirrer rod was inserted into the melt, positioned just below the surface of the melt and rotated at 500 rpm. Aluminum alloy slurry was bottom poured into preheated cast iron molds. The alloy was shaped in the form of cylinder with 35 mm outer diameter and a height of 210 mm. Billets of size ϕ32 mm × 50 mm were machined from these cylindrical rods and these billets were subjected to two stages of extrusion.

2.2. *Extrusion of aluminum alloy*

Extrusion process was carried out in ENKAY universal testing machine (UTM) of 600 kN capacity. The extrusion die was heated to the required temperature in a pit-type furnace. Once the die had attained the desired temperature, a period of 30 min, was allowed to elapse before the extrusion was carried out. This time is long enough to allow the billet to reach a steady-state temperature. The sizes of the billet material after first and second stage extrusions were ϕ28 mm × 60 mm and ϕ24 mm × 85 mm, respectively. The photograph of specimens subjected to different levels of extrusion is shown in Fig. 1 along with the as-cast specimen.

2.3. *Hot compression test*

In order to determine the stress–strain behavior of the alloy, uniaxial one-hit hot compression test was carried out using precise digital controller-servo equipped universal testing machine. One-hit hot compression test was conducted at different temperatures of 373, 473, 573, 673, and 773 K and different strain rates of 0.001, 0.01 and 0.1 s^{-1}, up to a strain of 0.5. Five samples were tested for each temperature–strain rate combination and mean values of stress and strain were considered for further analysis.

Fig. 1 – Photograph of specimens with different levels of extrusion (left to right: $\varepsilon = 0$, $\varepsilon = 0.266$, $\varepsilon = 0.305$).

Cylindrical specimens of size ϕ24 mm × 24 mm were used. Powdered molybdenum disulphide was used as lubricant up to 573 K and powdered graphite was used as lubricant for temperature ranging from 673 to 773 K. These colloidal powders were laid between punch and specimen for minimizing the friction. Samples were then heated to the test temperature. After heating, the samples were held at the test temperature for 5 min. and then hot compressed up to a strain of 50% [3]. True stress values were recorded using a pressure transducer with a resolution of 0.5 N. The microprocessor controlled UTM machine is equipped with inbuilt strain gauge for instantaneous strain measurement and interfaced with a Wincom software installed computer. The software generates the load and displacement curve with data points at the specified data logging rate. This information was used to develop the flow curves. The photographic image of the samples, hot compressed at different strain values, is shown in Fig. 2.

3. Results and discussion

3.1. *Flow behavior*

The flow stress vs flow strain curves of the aluminum alloy obtained at various temperatures and strain rates up to a height reduction of 50% are shown in Fig. 3.

In all these curves, the stress increases linearly with increase in strain up to a particular strain value and thereafter slows down and saturates with or without a slight dip in value. In Fig. 3(a), at 373, 473 and 573 K, the flow stress increases with strain initially and gently approaches a steady value with further increase in strain. The initial increase in stress may be attributed to the increase in dislocation density due to strain hardening. This type of flow curve is referred as dynamic recovery type of flow curve. Dynamic recovery is the only softening mechanism occurring under this process condition [4,5]. In case of 673 and 773 K the curve exhibits a slight dip in flow-stress value after reaching the peak stress. It can also be observed that the flow stress increases initially at a slower rate compared to that at lower temperatures. This happens because of the reason that the dynamic softening dominates over work hardening at higher temperatures [6,7]. The flow curve drops continuously until the balance between work hardening and dynamic softening is achieved. This pattern of the curve indicates the occurrence of dynamic recrystallization. Further, a reduction in stress value can be observed for an increase in temperature. This happens since movement of dislocations is favored by thermal activation at higher deformation temperatures [8,9].

Comparing the curves with same temperature in Fig. 3(a)–(c), it can be observed that the flow stress decreases with decreasing strain rate. As strain rate is decreased, the