Hot deformation activation energy of a 5E83 alloy prepared with centrifugal casting

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Abstract: 5E83 aluminum pipe was produced with centrifugal casting, the hot deformation were performed on the inner, middle, and outer layers of the pipe, the hot deformation activation energy Q were calculated. The results revealed that the hot deformation flow stresses exhibited increase tendency along with the inner, middle, and outer layer, the hot deformation activation energy Q increased from 164.5MPa for the inner layer to 197.6 and 214.9MPa for the middle and the outer layer respectively. Along with the layer of inner, middle, and outer, the solid solution level increased and the grain size decreased. Correspondingly, the solid solution hardening became stronger and the grain refinement mechanism was enhanced, resulting in the increased hot deformation flow stresses and activation energy Q.

1. Introduction
5E83 aluminum pipe is primarily used in the marine industry due to its excellent corrosion resistance, especially to seawater [1]. The conventional processing of 5E83 aluminum pipe could be divided into Direct Chill (DC) casting [2] and deformation such as extrusion [3].

The process of DC casting and extrusion is advantageous on the well-developed technology. However, aluminum industry is still looking for improving the economic advantage in terms of productivity to shortening the processing. There are also issues of defects such as coarse primary intermetallics and huge grains in the core of larger scale ingots in some alloys with high concentration of alloying elements [2].

Centrifugal casting is a process that uses centrifugal force to cast cylindrical parts. Fig. 1 shows a schematic of centrifugal casting, molten metal is poured into a rapidly spinning cylindrical mold in which centrifugal force drives the molten metal towards the mold walls as the mold fills. With all the molten metal in the mold, the mold remains spinning as the metal cools. Solidification begins at the mold walls and proceeds inwards until the completion of solidification.
2. Experimental

Investigations were conducted using an Al-4.55Mg-0.67Mn-0.39Er-0.10Zr 5E83 alloy. Centrifugal casting was conducted using a self-developed equipment. For the centrifugal casting process, the mold was coated with self-developed coating, the temperatures of smelting and casting were set as 725 and 700°C, respectively, the rotational speed was set as 800r/min. Cast pipe with dimension of 250mm length, 200mm outer diameter and 30mm thickness was prepared. Then after, homogenization at 425°C for 6h was performed.
After the homogenization, cylindrical specimens with diameter of 10 mm and length of 15 mm were taken from the homogenized pipe, as is shown in Fig. 2. Uniaxial hot compression tests were performed using an MMS-300 thermal simulator. The deformation temperatures were 400, 450, 500, and 550 °C, while the strain rates were 1, 0.1, 0.01, and 0.001 s⁻¹, the specimens were deformed to a total true strain of 0.5.

To analyze the microstructures, an optical microscope (Leica DMi5000M) was used for the microstructural observations. Chemical concentration of the inner, middle, and outer layer of the cast pipe was analyzed using spectrophotometry. Anode coating was carried out on the deformed samples, and polarization microscope (DMI5000M) was used for the grain structures observations.

![Fig. 2 Schematic of the specimens for hot deformation taken from the casting pipe.](image)

### 3. Results

#### 3.1. Flow stress of hot deformation

Fig. 3 shows a typical stress–strain curve of inner layer sample under the exemplary hot deformation condition of 400°C and 1 s⁻¹. The flow stress raised quickly at the beginning of the hot deformation until a yielded plateau was reached. After then the flow stress increased only slightly and a peak flow stress was generated. Subsequently, the flow stress decreased smoothly until the end of the deformation. The peak stress was identified as the tangent point on the flow curve by a horizontal dot line.

![Fig. 3 Stress–strain curve of inner layer sample under the hot deformation condition of 400°C and 1 s⁻¹.](image)
All the peak stresses of the inner, middle, and outer layers at all the deformation conditions were obtained and are plotted in Fig. 4 as functions of the deformation temperature and strain rate. Under the given deformation conditions, the peak flow stress increased with the decreasing strain rates and with the decreasing deformation temperatures. The overall tendency about the peak flow stress of the inner, middle, and outer layers was similar, but still slight differences in the peak stress could be distinguished, for instance, the flow stress at the 400°C/1s\(^{-1}\) condition exhibited an increase tendency from the inner to the outer layer.

Fig. 4 Peak flow stress of (a) inner, (b) middle, (c) outer layers.

3.2. Constitutive analyses
The hyperbolic-sine equation, proposed by Sellars and Mc Tegart [6], was widely used to demonstrate the relationship between the strain rate, deformation temperature, and flow stress:

\[ Z = \dot{\varepsilon} \exp \left( \frac{Q}{RT} \right) = A \sinh(\alpha \sigma)^n \]  

where \( Z \) represented the Zener–Hollomon parameter, \( \dot{\varepsilon} \) represented the deformation strain rate, \( n \) and \( A \) were material constants, \( \alpha \) was the stress multiplier, \( \sigma \) was the flow stress (MPa), \( Q \) was the activation energy for hot deformation (kJ/mol), \( R \) was the universal gas constant (8.314 J/mol K), and \( T \) was the deformation temperature (K). The experimental flow stress data for the inner layer were used as an example to derive the activation energy \( Q \) and material constants. The flow stress, \( \sigma \), was obtained using the peak stress. The stress multiplier, \( \alpha \), was defined as \( \alpha = \beta/n_1 \), where \( \beta \) and \( n_1 \) were evaluated using the mean slopes of the plots of \( \ln \dot{\varepsilon} - \sigma \) and \( \ln \dot{\varepsilon} - \ln \sigma \), respectively, for the range of experimental deformation temperatures. The mean values of \( \beta \) and \( n_1 \) were determined using the results in Fig. 5, while \( \alpha \) of inner layer was calculated to be 0.027 MPa\(^{-1}\).
Differentiating Eq. (1) yields the following:

\[ Q = R \left[ \frac{\partial \ln \dot{\varepsilon}}{\partial \ln [\sinh(\alpha \sigma)]} \right] \frac{\partial \ln [\sinh(\alpha \sigma)]}{\partial (1/T)} \bar{\dot{\varepsilon}} = RnS \]  

(2)

where \( n \) is the mean slope of the plots of \( \ln \dot{\varepsilon} - \ln [\sinh(\alpha \sigma)] \) at various temperatures and \( S \) is the mean slope of the plots of \( \ln [\sinh(\alpha \sigma)] - 1/T \) at different strain rates. The relationship between \( \ln \dot{\varepsilon} \) and \( \ln [\sinh(\alpha \sigma)] \), derived using the measured flow stresses (Fig. 4), was calculated (Fig. 6a). The mean value of the slopes at the four different deformation temperatures, \( n \), was then calculated to be 3.14. In addition, the relationship of \( \ln [\sinh(\alpha \sigma)] - 1/T \) is plotted in Fig. 6b. The mean slope \( S \) at various strain rates was 6.31. The activation energy \( Q \) could then be calculated by Eq. (2), yielding a value of 164.5 kJ/mol for inner layer.

The application of natural logarithm on both sides of Eq. (1) yields,

\[ \ln Z = \ln A + n \ln [\sinh(\alpha \sigma)] \]  

(3)

where \( \ln (A) \) is obtained as the intercept of the plot of \( \ln Z - \ln [\sinh(\alpha \sigma)] \), as shown in Fig. 7.
In a similar manner, the material constants $A$, $n$, and $\alpha$ and activation energies $Q$ were calculated according to Eqs. 1–3 for the middle and outer layers, as shown in Table 1. From the inner layer to the middle and outer layer, $\alpha$ decreased whereas $n$, $A$, and $Q$ increased. Among the material constants, the activation energy for hot deformation $Q$ is an important indicator of the difficulty degree of plastic deformation. The $Q$ value of the inner, middle, and outer layers were 164.5, 197.6, and 214.9 kJ/mol, respectively, indicating the plastic deformation became more difficult from the inner layer to the middle and outer layer of the 5E83 pipe.

| Positions    | $\alpha$ (MPa$^{-1}$) | $n$   | $A$ (s$^{-1}$) | $Q$ (kJ/mol) |
|--------------|------------------------|-------|----------------|--------------|
| Inner layer  | 0.027                  | 3.14  | 4.2x10$^9$     | 164.5        |
| Middle layer | 0.024                  | 3.56  | 5.8x10$^{11}$  | 197.6        |
| Outer layer  | 0.022                  | 3.84  | 1.1x10$^{13}$  | 214.9        |

3.3 Microstructures
The as-cast microstructure of the experimental alloy is shown in Fig. 8. As indicated, it was composed of aluminum dendrite cells, and intermetallic distributed along the dendrite boundaries. Besides, the intermetallics exhibited a tendency that the size declined and the fraction decreased along with the inner layer to the middle and outer layers.

Fig. 7 Relationship between $\ln Z$ and $\ln[\sinh(\alpha \sigma)]$. 
The concentrations of the main alloying elements were tested and the results are shown in Table 2. The concentration of Mg and Er decreased from the outer layer to the middle and inner layer. For instance, the actual concentration of Mg and Er of the outer layer were 5.5 and 0.34%, which were higher than the designed concentration of 4.8 and 0.3%, respectively; in contrast, the actual concentration of Mg and Er of the middle and inner layers are lower than those of the designed concentration.

| Design concentration | Mg (w.% ) | Er (w.% ) |
|----------------------|-----------|-----------|
| Inner                | 4.7       | 0.24      |
| Middle              | 4.8       | 0.26      |
| Outer               | 5.5       | 0.34      |

Microstructures of the experimental alloy after deformation are shown in Fig. 9. In general, mainly elongated grains perpendicular to the compression direction were observed in all deformed samples. Nonuniform deformation was observed, the degree of deformation strain was most severe at the region of the center of sample, while the position far from the center of the sample exhibited the lower degree of deformation. Besides, the grain size of the inner layer was about 344.9 μm, it decreased to 364.9 and 422.7 μm in the middle and outer layer, respectively.
4. Discussion

The innovation of this study lies in the manufacturing a wrought 5E83 alloy pipe using centrifugal casting that usually be used to fabric casting alloys, and the pipe was subsequently generated to the hot deformation, in order to investigate the hot deformation behavior and provide theoretical basis for the extrusion. The focus was placed on the hot deformation activation energy Q and microstructures. In practice of hot extrusion process for aluminum alloys, the hot deformation flow stress, which determining activation energy Q, is a key factor for the process in terms of productivity as a given press can only provide a certain press force. A high flow stress is unpreferable since it is difficult to conduct extrusion and resulted in a worsen surface quality of the pipe. A reduced flow stress results in a lower temperature increase during extrusion, which can effectively increase the extrusion speed at which surface defects are encountered [13].

The experimental alloy possessed a tendency that hot deformation flow stress and activation energy Q increased from the inner layer to the middle and outer layer. According to the microstructure, the increased grain size along with the outer to inner layer could be attributed to the solidification of the centrifugal casting. During centrifugal casting, the solidification takes place at the mold when the temperature of the melt decreases to the solidification temperature, hereby the outer layer of the casting pipe forms [14]. Along with the ongoing of the solidification, solidification heat is released and the cooling rate of the solidification declines accordingly, which may result in the coarsening of the grains [15]. While at the end of solidification when the inner layer is formed, the under cooling become even lower, leading to the larger grains comparing with the middle layer.

According to the grain refinement hardening mechanism [15], the smaller grain size of the outer layer provided overall higher level of dislocation piles-up and stress accumulation near the grain boundaries during hot deformation [16], leading to the overall flow stress. While for the middle and inner layers, the grain refinement hardening effect was weaken due to the smaller grain sizes, therefore, the flow stress level declined ascendingly.

Another aspect related to the hot deformation flow stress was solid solution level. The concentration of the alloying elements Mg and Er decreased from the outer layer to inner layer (Table 1), indicating that, at the outer layer, a stronger solid solution strengthening effect was exerted. Furthermore, the intermetallics of outer layer was in the smaller size and lower fraction, which further resulted in a higher level of solid solution level in Al matrix. Despite the homogenization performed after casting, it was not able to achieve a macro diffusion for alloying elements from inner layer to outer layer. In this case, the stronger solid solution strengthen at the outer layer was believed to be another factor attributed to the higher hot deformation flow stress and activation energy Q.

To sum up, the increased flow stress and activation energy Q from the inner layer to the outer layer of the casting pipe during hot deformation was resulted from two aspects, the stronger grain refinement effect caused from the smaller grain size of outer layer and the enhanced solid solution strengthening mechanism provided by the higher solid solution level of alloying elements at the outer layer.
5. Conclusion
(1) The hot deformation was performed on the inner, middle, and outer layers of the 5E83 aluminum pipe produced with centrifugal casting, the material constants and activation energies $Q$ for hot deformation were calculated using the hyperbolic-sine constitutive equation and experimental peak flow stress data.

(2) The hot deformation flow stress exhibited increased tendency from the inner layer to the middle, and outer layer; the hot deformation activation energy $Q$ increased from 164.5MPa for the inner layer to 197.6 and 214.9MPa for the middle and outer layer, respectively.

(3) Along with the layer of inner, middle, and outer, the solid solution level increased and the grain size decreased; correspondingly, the solid solution hardening became stronger and the grain refinement mechanism was enhanced, resulting the increased hot deformation flow stress and activation energy $Q$.

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