Original Article

Hot deformation and processing maps of Al–Zn–Mg–Cu alloy under coupling-stirring casting

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Article history:
Received 2 May 2018
Accepted 7 August 2018
Available online 25 October 2018

Keywords:
Al–Zn–Mg–Cu alloy
Microstructure
Processing map
Stress–strain curves
Coupling-stirring

Abstract

Compression tests of direct-chill (DC) casting and coupling-stirring (CS) casting Al–Zn–Mg–Cu alloy have been performed in the strain rate range from 0.01 s−1 to 10 s−1 and the temperature range from 320 ◦C to 480 ◦C. The effects of DC casting on the processing map, flow behavior and deformation kinetic have been discussed. The result shows that the uniformity of the critical stress, the peak stress and the steady-state stress have been improved and the flow stress has been decreased significantly using the coupling stirring. The processing maps shown that the suitable deformation condition for the DC casting alloy is 0.01–0.1 s−1 and 380–480 ◦C, and the suitable deformation condition for the CS casting alloy is 0.01–0.05 s−1 and 320–480 ◦C and 0.05–0.5 s−1 and 400–480 ◦C. The activation energies at the deterministic domains of the DC casting alloy and CS casting alloy are 210 kJ/mol and 185 kJ/mol, respectively.

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1. Introduction

The Al–Zn–Mg–Cu aluminum alloys are very attractive materials to be widely employed in the aeronautics and astronautics manufacturing, auto manufacturing, and advanced weapons manufacturing due to some advantageous properties [1–3]. However, the disadvantages such as the extreme hot cracking tendency, obvious macro and micro segregation, serious porosity defect and so on, limit the expansion of the application [4–7]. To solve this problem, there are typical cases, such as casting, refining, and electromagnetic (CREM), that was initially proposed by Vives [8] and low-frequency electromagnetic casting (LFEC) that was subsequently developed by Cui [5]. Coupling stirring (CS) technology combining the characteristics of mechanical stirring and electromagnetic stirring is a advanced technique and has been proposed by Wang [9].

The processing map founded on DMM [10], which was widely used in evaluating hot workability [11] has been
proposed by Prasad and colleagues recently [12,13]. The power dissipation should be considered during the hot deformation work and the dissipation efficiency (\(\eta\)) related to the strain rate sensitivity (m) can be given by [14]:

\[
n = \frac{2m}{m + 1}
\]  

(1)

The power dissipation map is given by the variation of the efficiency \(\eta\) with strain rate and deformation temperature, and is a contour map depicting the efficiency contour lines, which exhibits the power dissipation through organization evolution under different strain rates and different deformation temperature. The flow unstable map revealed microstructural instabilities is given by the instability value applied to DMM. The principles of the continuum criterion and the maximum rate of production entropy [15] are used in the present of the instability criterion which have been proposed in many investigations [16–18]. The instability criterion can be expressed by the equation [19]:

\[
\zeta (\dot{\varepsilon}) = \frac{\alpha \ln \left( \frac{m}{m+1} \right)}{\beta \ln \dot{\varepsilon}} + m < 0
\]  

(2)

The negative values of the parameter \(\zeta (\dot{\varepsilon})\) delineate instability regimes according to the strain rate and deformation temperature. The processing map can be displayed by superimposing the power dissipation map and the flow instability map.

The deformation mechanisms in different strain rates and temperatures can be predicted by the processing map, and the flow unstable zones can also be received and should be avoided strictly during deformation. In additional, by analyzing processing map, the deformation parameters can be optimized accordingly and finally, the structures and properties is also possible to control and the failure rate is reduced in deformation process, and the quality and reliability of the products is improved. The most noteworthy is that the effect of the melt treatment technology on the deformation mechanisms, the unstable deformation zones, the optimum deformation parameters of the material will be revealed through comparing the hot deformation and processing maps of the alloy before and after treatment with the melt treatment technology, which have not been studied until now.

2. Methods

In this study, the composition of the test alloy was: Al–5.0%Zn–2.5%Mg–1.8%Cu (in wt.%) and the cylindrical specimens of 314 mm in diameter were utilized. The materials was melted in a MF smelting furnace under the casting temperature of 760 °C, the slag was removed, and the grain refiner of 0.2%Al–5Ti–1B (in wt.%) was added. Under the pouring temperature of 730 °C, the ingots were obtained by coupling-stirring (CS) casting that the schematic is shown Fig. 1 and direct-chill (DC) casting process respectively. During the casting process, the water flow rate was 9.8 m²/h, the casting speed was 72 mm/min, and for CS casting, the current intensity was 90A, the frequency was at the rate of 12 Hz, and the stirring speed was 110 rad/min. Homogenizing treatment were conducted under the condition of 470 °C for 24 h and then air cooling for the ingots. The hot compression specimens with dimension of φ10 mm × 15 mm were cut from the ingots prepared by DC casting and CS casting. The specimens were compression deformed in the strain rate range of 0.01–10 s⁻¹, the temperature range of 320–480 °C and at the true strain of 0.7 and water-quenched on the Gleebie-1500 experimental machine. Two flake graphitees were set between the crossheads and the specimens in order to reduce the deformed friction. For all specimens, the heating time and holding time is 1 min and 3 min respectively in order to promote uniform temperature of these specimens prior to deformation.

The adiabatic temperature rise which affected the accuracy of flow stress at setting deformation conditions must be existed during the deformation. Especially for high strain rate (≥1 s⁻¹), the flow stress difference could not be ignored. Furthermore, the influence of fraction on the flow stress values is important and should be considered in investigations. The influence can be expressed by the equation [20]:

\[
\sigma = \frac{1}{2} \left[ \exp \left( \frac{2\mu R}{h} \right) - \frac{2\mu R}{h} - 1 \right] \left( \frac{2hR}{P} \right)^2
\]  

(3)

where \(\sigma\) and \(P\) is the corrected and uncorrected flow stress, \(R\) and \(h\) are the specimen instantaneous radius and height during deformation, and \(\mu\) is the friction coefficient which

![Fig. 1 - Schematic diagram of coupling-stirring casting.](image-url)
is determined according to the amount of barreling for each specimen [21] and is calculated as follows:

\[ b = 4 \frac{\Delta R}{R_1} \frac{h_1}{\Delta h_1} \tag{4} \]

\[ \mu = \frac{(R_1/h_1) b}{(4/\sqrt{3}) - (2b/3\sqrt{3})} \tag{5} \]

\[ R_1 = R_0 \sqrt{\frac{h_0}{R_1}} \tag{6} \]

where \( h_1 \) is the final height of the specimen, \( \Delta h_1 \) is the difference between final and initial heights of the compressing specimen, \( \Delta R \) is the difference between the minimum radius (\( R_M \)) and maximum radius (\( R_M \)) of the deformed specimen. Instruction chart of hot deformation of the alloy is shown in Fig. 2.

![Instruction chart of hot pressing deformation for Al–Zn–Mg–Cu alloy.](image)

**3. Results**

**3.1. Stress uniformity**

The sampling positions of the test alloys were shown in Fig. 3(a). Fig. 3(b) demonstrated the flow stress curves of the alloys deformed at different positions of the DC casting alloy and the CS casting alloy at the deformation condition of 0.01 s\(^{-1}\) and 440 °C. Typically, the trend of the curves for all marking positions decreased obviously under CS casting. The result of the true stress–true strain for the two types of casting alloy showed that the CS-cast alloy exhibited better high temperature plastic deform-ability. Another outstanding exhibition from Fig. 3(b) was that the difference of the flow stresses of DC casting ingot in cross section was tremendous, but the difference of the flow stresses of CS casting ingot in cross section was small. Furthermore, Fig. 3(b) revealed that Al–Zn–Mg–Cu alloy underwent local dynamic recrystallization at the strain rate and setting temperature. The initiation of DRX mainly depends on the dislocation density and dislocation distribution during deformation. The stress \( \sigma_c \) was used to describe the initiation of DRX and can be obtained as follows:

\[ \theta = \left( \frac{\partial \sigma}{\partial \varepsilon} \right)_{T} \cdot \frac{\partial \varepsilon}{\partial \sigma} = 0 \]

The initiated DRX can be expressed by the minimum point in the \(-\partial \sigma/\partial \varepsilon – \sigma\) curve in Fig. 4. From the flow stress dependence of the strain hardening rate at different conditions, it can be exhibited that CS casting alloy had proximity in the critical

![Positions marking in ingots (a) and flow stresses of the DC casting and CS casting ingots (b).](image)

![Flow stress dependence of the strain hardening rate at different conditions: (a) DC casting alloy; (b) CS casting alloy.](image)
stress values of the initiation of DRX for the positions of 1, 2, 3, 4, 5 than DC casting alloy. Table 1 listed the characteristic stress values of different positions of DC casting and CS casting ingots. σm and σss are the peak stress and the steady-state stress under DRX, respectively. It is obvious that the differences between the highest and the lowest values of σm, σss and σc were reduced obviously under CS casting. That is to say, the CS casting is very helpful in improving the uniformity of the flow stress value of the alloy, which leads to uniform processing property and service performance, and what is more, small energy consumption and high material utilization can be produced.

3.2. Flow curves

Via the data compensated for friction and temperature, the true stress–true strain curves for the alloy in the strain rate range of 0.01–10 s⁻¹ and the temperature range of 320–480 °C are shown in Fig. 5. For all of the deformation conditions of DC casting alloy and CS casting alloy, the deformation conditions including temperature, strain rate and true strain can directly affect the flow characteristic. The trend of the curves exhibits a typical characteristic that the true stress value increases to a maximum value before reaching a peak stress within a small strain range then decreases with the true strain. Actually this phenomenon is caused by the dynamic competition between the softening and the working hardening. The softening mechanisms include the DRX, the DRV, the counteraction of unlike dislocation and the dislocation rearrangement, while the working hardening mechanisms including the dislocation reduplication, tangle and pileup [22]. Generally, the flow stress decreased with temperature and increased with strain rate. When the strain rate increased, the working hardening is strengthened because the number and motion rate of dislocations improved, what is more, the softening rate decreased because of the decrease of the reaction rate and climbing of dislocations. However, when the deformation temperature increased, the softening caused by DRX and DRV improved, and the critical shear stress decreased.

Based on the curves characters of DC casting alloy and CS casting alloy, the flow stress variety law with the temperature, strain rate and strain is the same. The effect of coupling stirring technology on flow stress at the setting temperatures and strain rates cannot be exhibited completely from Fig. 5(a) and (b) besides a phenomenon that the CS casting alloy holds lower flow stresses at same deformation conditions than the DC casting alloy, indicating that the alloy would exhibit superior workability. It is necessary to further discuss the flow behavior evolution characteristic and its influence on the processing performance under the coupling stirring technology.

3.3. Processing maps

3.3.1. Establishment of processing maps

The flow stresses compensated for friction and temperature were used to build power dissipation maps and instability maps by Eqs. (1) and (2), respectively. The relationship between

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**Table 1 – Characteristic stress values of different positions of DC casting and CS casting alloy.**

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Positions</th>
<th>σm/MPa</th>
<th>σss/MPa</th>
<th>σc/MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC casting</td>
<td>Point 1</td>
<td>33.39</td>
<td>32.51</td>
<td>25.31 (min)</td>
</tr>
<tr>
<td></td>
<td>Point 2</td>
<td>31.76 (min)</td>
<td>29.86 (min)</td>
<td>30.21</td>
</tr>
<tr>
<td></td>
<td>Point 3</td>
<td>32.39</td>
<td>31.52</td>
<td>26.74</td>
</tr>
<tr>
<td></td>
<td>Point 4</td>
<td>34.72 (max)</td>
<td>33.72 (max)</td>
<td>31.08 (max)</td>
</tr>
<tr>
<td></td>
<td>Point 5</td>
<td>33.59</td>
<td>32.74</td>
<td>28.98</td>
</tr>
<tr>
<td>CS casting</td>
<td>Point 1</td>
<td>30.64</td>
<td>29.13</td>
<td>26.16</td>
</tr>
<tr>
<td></td>
<td>Point 2</td>
<td>31.06 (max)</td>
<td>29.21</td>
<td>26.03</td>
</tr>
<tr>
<td></td>
<td>Point 3</td>
<td>30.00</td>
<td>29.52 (max)</td>
<td>26.97</td>
</tr>
<tr>
<td></td>
<td>Point 4</td>
<td>28.58 (min)</td>
<td>28.39 (min)</td>
<td>25.13 (min)</td>
</tr>
<tr>
<td></td>
<td>Point 5</td>
<td>29.79</td>
<td>29.20</td>
<td>27.81 (max)</td>
</tr>
</tbody>
</table>

---

Fig. 5 – True stress-true strain curves compensated for friction and temperature for Al–Zn–Mg–Cu alloy at different temperatures and strain rates: (a) DC casting alloy; (b) CS casting alloy.
Fig. 6 – Efficiency maps of power dissipation for the DC casting alloy (a) and the CS casting alloy (b) at a strain of 0.7.

![Image of efficiency maps](image)

Fig. 7 – Different instability zones at the different strains for DC casting alloy (a) and CS casting alloy (b).

![Image of instability zones](image)

\[ \lg(\eta) \text{ and } \lg(\dot{\varepsilon}) \text{ described by three order polynomial fitting can be expressed as follows:} \]

\[ \lg(\dot{\varepsilon}) = a + b\dot{\varepsilon} + c(\dot{\varepsilon})^2 + d(\dot{\varepsilon})^3 \quad (7) \]

where \(a, b, c\) and \(d\) are the constants of the material depending on temperature. \(m\) is obtained as follows:

\[ m = \frac{\partial (\lg(\dot{\varepsilon}))}{\partial (\lg(\dot{\varepsilon}))} = b + 2c\dot{\varepsilon} + 3d(\dot{\varepsilon})^2 \quad (8) \]

Based on Eqs. (8) and (1), \(\eta\) can be calculated and described with a three-dimensional plot as shown in Fig. 6. Based on Eqs. (8) and (2), \(\zeta(\dot{\varepsilon})\) can be calculated by the expression:

\[ \zeta(\dot{\varepsilon}) = \frac{\partial g}{\partial \dot{\varepsilon}} \left( \frac{m + \dot{\varepsilon}}{m + \dot{\varepsilon}} \right) + m \frac{b + 2c\dot{\varepsilon}}{a + 1 + b\dot{\varepsilon} + c(\dot{\varepsilon})^2} + a + b\dot{\varepsilon} + c(\dot{\varepsilon})^2 < 0 \quad (9) \]

The variations of \(\zeta(\dot{\varepsilon})\) with strain rate and temperature changes constitute the instability maps which are shown in Fig. 7.

3.3.2. Processing efficiency maps

The 3D efficiency maps obtained at the strain of 0.7 for DC casting alloy and CS casting alloy are shown in Fig. 6. The different contours and color levels represent the different efficiency values which describe the relative rate of internal entropy production during hot deformation and the dissipation due to the microstructure change with deformation conditions [23]. When \(\eta\) is higher, the performance of formed organization can be improved better because of dynamic recrystallization, dynamic recovery and superplasticity [24].

From the processing efficiency map of the DC casting alloy as shown in Fig. 6(a), it can be found that three valley efficiency domains appear given below: (1) 5–10 s\(^{-1}\) and 360–440 °C (\(\eta < 0\)); (2) 1–10 s\(^{-1}\) and 320–340 °C (\(\eta < 0.12\)); (3) 0.01–0.02 s\(^{-1}\) and 380–410 °C (\(\eta < 0.25\)). Two peak efficiency domains can be seen: (1) 0.01–0.1 s\(^{-1}\) and 420–480 °C (\(\eta > 0.35\)); (2) 0.01–0.02 s\(^{-1}\) and 320–360 °C (\(\eta > 0.3\)). One top efficiency occurs at 0.01 s\(^{-1}\) and 460 °C (\(\eta = 0.5\)).

From the processing efficiency map of the CS casting alloy as shown in Fig. 6(b), it can be found that three valley efficiency domains appear given below: (1) 8–10 s\(^{-1}\) and 400–480 °C (\(\eta < 0\)); (2) 2–10 s\(^{-1}\) and 320–340 °C (\(\eta < 0.12\)); (3) 0.01 s\(^{-1}\) and 420–480 °C (\(\eta < 0.33\)). One peak efficiency domains can be seen in the strain rate range of 0.05–0.5 s\(^{-1}\) and the temperature range of 420–480 °C (\(\eta > 0.39\)). One top efficiency occurs at 0.1 s\(^{-1}\) and 480 °C (\(\eta = 0.48\)).

After a contrast study, the peak efficiency domains for the two types of materials occurred at higher temperature conditions due to dislocation climbing and crossing more easily resulting in more power dissipation. Moreover, the red and yellow marked by black frames areas namely the high efficiency
value areas in the 3D efficiency maps of the alloy are expanded when the CS casting was implemented.

To the pursuit of more power dissipation owing to microstructure evolution for obtaining better formability, the strain rate and temperature corresponding to the peak efficiency in processing map should be selected as the optimum hot deformation parameters of the alloy. However, the deformation conditions corresponding to high $\eta$-values cannot always represent forming safety and the flow deformation property must be analyzed further combining instability criterion.

3.3.3. Processing instability maps

The instability maps describe the variation of the instability parameter $\zeta (\dot{\varepsilon})$ with the strain rate and temperature. The unsafe conditions for hot working in which the instability parameter is negative and the safe conditions in which the instability parameter is positive can be found out in the instability maps. The instability regions at different true strains are shown in Fig. 7, where the gray scale areas in the 3D instability maps indicate the unstable flow corresponding the deformation condition while the white areas indicate the safety deformation regions. As can be seen from Fig. 7(a) and (b), the zone of unstable flow changes for the DC casting alloy from the high strain rates and the middle temperatures to the high strain rates and the low temperatures, and the high strain rates and the high temperatures, from the low strain rates and the middle temperatures to the low strain rates and the low temperatures, from the high strain rates and the low temperatures to the high strain rates and the high temperatures with the increase of strain. The zone of unstable flow changes for the CS casting alloy from the high strain rates and the middle temperatures to the high strain rates and the low temperatures and the high strain rates and the high temperatures. In general, the flow instability regions for the two types of materials enlarge with the increase of strain.

After a contrast study, the CS casting alloy holds smaller flow instability regions at the same strain than the DC casting alloy, namely the coupling stirring technology enlarges the safe processing regions and improves the deformation mechanical including dynamic recovery, dynamic recrystallization, super-plasticity, and so on [23], indicating that the alloy would exhibit more excellent workability. It was previously reported that when the efficiency was about 0.30, the dynamically recovery happened, but the efficiency was above 0.30, the dynamically recrystallization happened [25].

3.3.4. Analysis of processing maps

The processing map of the alloy by DC casting and CS casting at the strain of 0.7 is shown in Fig. 8. The efficiency of power dissipation $\eta$ indicates the power dissipation result of microstructural evolution, and the material under the condition with high efficiency shows better processing properties. However the condition with high efficiency may exhibit the negative instability parameter, which the unstable flow deformation may also occur due to cracking, located plastic flow, or adiabatic shear bands. So the deformation conditions corresponding to the peak efficiency in safe processing domain in the processing map should be confirmed as the optimum processing parameters. Furthermore, the domains with very dense contour lines of high efficiency of power dissipation and close to the regions of unstable flow are considered as the metastable domains, which are unfavorable for controlling microstructures. The conditions under these domains are not good for consideration. Based on these basics, the suitable deformation condition for the DC casting alloy is in the strain rate range of 0.01–0.1 s$^{-1}$ and the temperature range of 380–480 °C and the optimum parameter for hot working is at the strain rate of 0.01 s$^{-1}$ and the temperature of 460 °C at the strain of 0.7. The suitable deformation condition for the CS casting alloy is in the strain rate range of 0.01–0.05 s$^{-1}$ and the temperature range of 320–480 °C, and in the strain rate range of 0.05–0.5 s$^{-1}$ and the temperature range of 400–480 °C, and the optimum processing parameter of the CS casting Al–Zn–Mg–Cu alloy is at the strain rate of 0.1 s$^{-1}$ and the temperature of 480 °C at the strain of 0.7.

In general, the effect of the CS casting on processing maps is revealed.

Firstly, the safe processing regions in the processing maps corresponding to safe deformation condition enlarge. It indicates that the coupling stirring technology improves the workability of Al–Zn–Mg–Cu alloy; for instance, the conditions at low deformation temperatures (in the temperature range of 320–360 °C) cannot be conducted until the coupling stirring technology is used.

Secondly, a wider platform in the 3D efficiency map and a sparse region in 2D efficiency map, which hold high efficiency, appeared after using the coupling stirring technology.
Fig. 9 – Variation of flow stress with strain rate at different test temperatures for the DC casting alloy (a) and the CS casting alloy (b) at a strain of 0.7.

Fig. 10 – Arrhenius plot showing the variation of logarithm of flow stress with inverse of test temperature at different strain rates for the DC casting alloy (a) and the CS casting alloy (b) at a strain of 0.7.

It indicates that the change of the deformation mechanism under these deformation conditions is not obvious with deformation conditions, which is of great benefit to controlling the microstructures and performances of the material.

3.4. Kinetics of hot deformation

The standard kinetic rate equation of the flow stress to strain rate and temperature is given as follows [26]:

\[ \dot{i} = A \sigma^n \exp \left( -\frac{Q}{RT} \right) \]  \hspace{1cm} (10)

where \( A \), \( R \), \( n \), \( Q \) and \( T \) are the material constants, the gas constant, the stress index, the activation energy and temperature respectively. The activation energy within the deterministic deformation can be evaluated through the equation, and furthermore the temperature and strain rate dependence of flow stress may analyzed by the Evolution formula as following:

\[ Q = nR \frac{\partial \ln \sigma}{\partial (1/T)} = 2.303nR \frac{\partial \sigma}{\partial (1/T)} \]  \hspace{1cm} (11)

where \( n \) is the stress exponent and \( n = 1/m \).

In order to discuss the hot deformation ability of the two Al–Zn–Mg–Cu alloys, one common domain from the processing maps corresponding to the same process parameter range was selected and is in the strain rate range of 0.01–0.5 s\(^{-1}\) and the temperature range of 400–480 °C as shown in the frame selected area in Fig. 8. The variation of flow stress with strain rate at different test temperatures for the DC casting alloy and the CS casting alloy is shown in Fig. 9 for calculating the strain rate sensitivities and the slopes of \( \log \sigma \) vs. \( (1000/T) \) curves is shown in Fig. 10 for calculating the activation energies [26]. The activation energies corresponding to the deterministic domains of the DC casting alloy and CS casting alloy are shown in Fig. 11 and are 210 kJ/mol and 185 kJ/mol, respectively. These values are higher than the anticipated
value for lattice self-diffusion in Al (144 kJ/mol) [27], which is because the duration time during test process is so short that there is only very limited additional precipitation. And from the data, the activation energy values under the deterministic domains for the CS casting alloy are lower than those for the DC casting alloy, which shows that the CS casting alloy has good deformation performance and is easy to be deformed, so the production cost can be saved and the utilization of the material can be improved.

4. Discussion

4.1. Physical field

In the coupling-stirring casting process, a time varying physical field caused by the intensive shearing forces in the melt is generated, which improves the uniformity of melt temperature and composition distribution.

In fluid theoretical research, the shear stress ($\tau$) is related to velocity and can be given by [28]:

$$\tau = \mu \frac{dv}{dy}$$  \hspace{1cm} (12)

where $\mu$ is the fluid viscosity coefficient, $v$ is the tangential velocity component, $y$ is the direction perpendicular to the flow direction of the fluid, $\frac{dv}{dy}$ is the velocity gradient perpendicular. Based on the coupling-stirring casting method, the shear stress ($\tau_{ele}$) for electromagnetic stirring and the shear stress ($\tau_{mec}$) for coupling stirring in Fig. 12 can be calculated by:

$$\tau_{ele} = \mu \frac{dv}{dy} = \mu \frac{v_{max} - v_{min}}{\Delta R}$$  \hspace{1cm} (13)

$$\tau_{mec} = \mu \frac{dv}{dy} = \mu \frac{V_{max} - V_{min}}{\Delta R}$$  \hspace{1cm} (14)

where $v_{max}$ and $v_{min}$ are the maximum and minimum tangential velocity component under the treatment of electromagnetic stirring in the area with the width of $\Delta R$. $V_{max}$ and $V_{min}$ are the maximum and minimum tangential velocity component under the treatment of taper tower mandrel stirring in the area whose width is $\Delta R$. If the two stirring method conducted simultaneously, the coupling shear stress ($\tau_{cop}$) can be calculated by:

$$\tau_{cop} = \mu \frac{dv}{dy} = \mu \frac{V_{in} - V_{out}}{\Delta R} - \mu \frac{(V_{max} - v_{min}) - (V_{min} - v_{max})}{\Delta R}$$  \hspace{1cm} (15)

$$\tau_{cop} = \mu \frac{V_{max} - V_{min}}{\Delta R} + \mu \frac{(V_{max} - v_{min})}{\Delta R}$$

It is obvious that the shear stress ($\tau_{cop}$) is the sum of the two stresses of $\tau_{ele}$ and $\tau_{mec}$. Besides, to CS casting method, a conical spiral stirrer is set in the melt center, and a narrow annulus gap which could avoid the weak stirring zone effectively is gained in order to always maintain high stirring intensity during melt treatment. Therefore, under the CS casting, a forced energy and species transfer occurs and is fit for heat and mass transfer quickly and uniform distribution.

Fig. 13 shows the temperature variations for DC casting and CS casting processing in the process of stable casting. From the figure, it can be seen that the temperature difference value for DC casting and CS casting are approximately 40°C and 1°C, respectively. Namely, the temperature during the CS casting process is obviously more uniform and the temperature field is improved observably by CS.
4.2. Microstructure

The microstructures at the 1/2 radius area of the DC casting and CS casting alloy are shown in Fig. 14. The results show that for the sample with DC casting, the microstructures are made of the coarse dendrites and however, the microstructures for the CS casting alloy are made of the fine equiaxed grains in the majority. There are many reasons that cause this phenomenon.

(1) The forced heat and mass transfer of the melt leads to super-cooling more quickly, which is propitious to reduce remelting of some nuclei caused by local overheating and form more fine and uniform crystal nuclei in the melt. So the CS casting process increases the effective nuclei during the solidification and the microstructures of the CS casting alloy are fine and uniform.

(2) The forced convection produces the collision and abrasion actions of the crystal nuclei and grains during the CS casting solidification process, which is helpful for refining, spheroidizing and homogenizing the primary crystals.

(3) The forced convection accelerates nuclei near the mold moving from mold to the bulk liquid and nuclei solidification front moving to center in order to gain more nuclei formed and improves nuclei uniform distribution for the CS casting. Based on the research about the break of secondary dendritic arm and block nucleation [29], it can be concluded that the phenomenon was contributed to form more nucleating center and increased the nucleation number.

(4) The forced convection reduces the temperature and compositional gradient of the melt during the melting and solidification process, which results in isotropic grain growth in the CS casting alloy and is helpful for refining and spheroidizing the primary crystals.

4.3. Hot workability

Microstructures determine various properties of the material. From previous studies, the change of the microstructures under CS casting is obvious, which results in dramatic effects on the hot workability of the experimental alloy.

By the CS casting, uniform grain size, grain shape and second phase are helpful for improving various properties uniform of the alloy, and that is not in question. Because uniform structure produces uniform boundary angle distribution, grain orientations, second phase distribution and quantity, dislocations motion resistance and so on, which will make further the density and number of dislocations, the slip style and direction, the time and degree of DRX and DRV in plastic deformation of alloys to uniform. Figs. 3 and 4 and Table 1 revealed that the flow stress and the initiation of DRX in the different positions of the cross section of the alloy was uniformed by CS casting. It has always been pursued of human beings, especially for large-scale ingots with high alloying components.

Moreover, another phenomenon that CS casting reduced obviously the flow stress (shown in Figs. 3 and 5) and deformation activation (shown in Fig. 11) was found from the experimental results and the reasons are manifold. The grain size is more uniform, the lattice distortion is small, which induces to decrease the flow stress under CS casting. As we all know, in the process of high temperature deformation, the grain boundary sliding occupies a more important position than the dislocation slip. Fine grain alloy due to larger grain boundary area per unit volume, which holds good plasticity in grain boundary at high temperature presents viscous flow. In addition, the fine and equiaxed grains decrease the resistance of grain rotation and grain boundary sliding, which are the main deformation mechanisms and decrease the energy barrier for further deformation. Therefore, the decrease of grain size results in the increase of grain boundary area per unit volume, which makes the grain boundary sliding easier and decreases the flow stress and deformation activation under CS casting.

Recrystallization nucleation usually occurs at the grain boundaries. The smaller the original grain size, the larger the energy storage after deformation, the larger the recrystallization nucleation rate and the lower the recrystallization temperature. For fine grain alloy, dynamic recrystallization volume fraction is higher than that of the coarse grain during hot deformation, which indicates that fine grain alloy exhibits better softening effect because dynamic recrystallization plays a softening effect. Therefore, the flow stress of CS casting alloy with more fine grain is lower than that of
DC casting alloy with more coarse grain, and the CS casting expands the safe working area and improves the processing performance.

5. Conclusion

(1) The uniformity of the flow stress, the peak stress, the steady-state stress and the critical stress of DRX along the whole cross section specimen is improved by the coupling stirring. The CS casting alloy holds lower flow stresses at the same deformation conditions than the DC casting alloy.

(2) Combining with the processing maps at the strain of 0.7, the suitable deformation condition for the DC casting alloy is 0.01–0.1 s⁻¹ and 380–480 °C and the optimum parameter is 0.01 s⁻¹ and 460 °C. The suitable deformation condition for the CS casting alloy is 0.01–0.05 s⁻¹ and 320–480 °C and 0.05–0.5 s⁻¹ and 400–480 °C, and the optimum parameter is 0.1 s⁻¹ and 480 °C.

(3) After using the coupling stirring technology, the safe processing regions in the processing maps enlarge. A wider platform in the 3D efficiency map and a sparse region in 2D efficiency map, which holds high efficiency, appears after using the coupling stirring technology.

(4) The activation energies at the deterministic domains of the DC casting alloy and CS casting alloy are shown to be 210 kJ/mol and 185 kJ/mol, respectively. The research shows that the CS casting alloy has good deformation performance and is easy to be deformed, so the production cost can be saved and the utilization of the material can be improved.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgments

Great thanks for the financial support to our work from the Project Funded by Doctoral Foundation Program of Southwest University of Science and Technology (No. 15zx7126) and China Postdoctoral Science Foundation (58 group, Grant No. 2015MS80799; 9 group, Grant No. 2016T90873).

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