Rare Metal Materials and Engineering
Volume 51, Issue 3, March 2022
Available online at www.rmme.ac.cn

Science Press

Cite this article as: Su Xin, Shen Shanzhong, Xu Jibo, et al. Thermal Formability of 7075 Alloy Strip Under Electric Pulse Rheo-rolling Process[J]. Rare Metal Materials and Engineering, 2022, 51(03): 850-857.

ARTICLE

Thermal Formability of 7075 Alloy Strip Under Electric Pulse Rheo-rolling Process

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Abstract: The microstructure and thermal formability of twin-roll cast 7075 alloy strips prepared with and without electrical pulse (EP) of 5 mm in thickness were investigated by hot tensile tests under the condition of deformation temperature of 250~350 °C and strain rate of 0.001~0.01 s^{-1}. The related EP current parameters are as follows: the single cycle pulse width is 0.005 s; the pulse peak current is 300 A. The results show that the EP current effectively promotes the grain refinement and the precipitate homogeneousness, because the electromagnetic oscillation enhances the solute mixing ability during solidification. Meanwhile, the rolling textures of face-centered cubic (fcc) 7075 Al strips have the {423}<144> orientation. After EP current modification, the orientation of 7075 Al strips is {421}<216>. The peak flow stress of the 7075 alloy strips prepared with EP current is about 1.1~1.3 times larger than that of the original 7075 alloy strips. The electron back-scattered diffraction analysis shows that EP current can effectively improve the preferred distribution of the grains by promoting the dynamic recrystallization. Furthermore, the hyperbolic sine equation and the constitutive model with Zener-Holloman parameter are established based on the analyses. Besides, according to the fracture morphology, the EP current is beneficial to improve the mechanical properties of 7075 alloys at elevated temperature. Finally, the processing maps are established and the proper hot working parameters are designed as the temperature range of 290~330 °C and the strain rate of 0.001~0.002 s^{-1}.

Key words: aluminum alloy; twin-roll cast; pulse electrical field; high temperature deformation; thermal formability

Currently, with the development of the economic globalization, the lightweight design is preferentially considered in many industries and fields due to the energy crisis, such as aerospace, manufacturing, and automotive[1]. The 7000 series alloys consist of high alloys, resulting in the difficult elimination of structural defects[2,3]. Hence, the forming and machining techniques of 7000 series alloys have been widely investigated.

The high-cost and serious pollution during conventional casting-hot rolling of Al alloy strips are gradually solved by twin-roll casting (TRC) technique. Su[4,5] and Sun[6] et al found that excellent qualities of 7075/6181 alloys are achieved by the introduction of pulse current during semisolid solidification due to the improved solute mixing ability. He et al[7] studied the microstructure and mechanical properties of Al-Mg-Si alloys after sub-rapid solidification under different external fields, and found that the electromagnetic braking and electromagnetic shocking effects are induced by the static magnetic field and pulsed current field, respectively. The uniform microstructure and composition distribution are improved, and the mixing capacity and solid solubility of the alloy elements in the matrix are enhanced. Zuo et al[8] conducted the low frequency electromagnetic casting (LFEC) process to prepare the flat ingots of 2524 alloy, and found that the flat ingot has a finer and more uniform microstructure transformed from the dendrite and rosette-like shape to the equiaxed structure. It is also observed that the segregation in the ingot center is obviously reduced. Zhang et al[9,10]

Received date: March 13, 2021
Foundation item: Postdoctoral Research Initiation Funding of Zhejiang Province (ZJ2021082); Natural Science Foundation of Liaoning Province (20170520310)
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established an accurate comprehensive mathematical model to describe the interaction of the multiple physics fields during the conventional direct chill casting and LFEC process. It is found that during LFEC process, the casting stress in the billets is remarkably reduced and the crack is effectively reduced.

However, the 7000 series alloys are generally composed of numerous multiphases, including the coarse brittle precipitates, such as Al_7Cu_2Fe, Al_2CuMg, and (Fe, Mn, Cu)Al_6, resulting in poor formability of TRC strips at room temperature[11]. Kou et al[12] studied the flow stress behavior of 7150 aluminum alloy during hot compression at elevated temperatures, and found that the flow stress is increased firstly with increasing the strain and tends to be constant after reaching the peak value, which can be represented by the hyperbolic sine equation with the Zener-Hollomon parameter. Cerri et al[13] conducted a comparative research of 7012 and 7075 alloys after hot forming process, and revealed that the peak flow stress of alloys prepared by specific pretreatments is related to the strain rate based on the hyperbolic sine equation. Li et al[14] studied the flow softening behavior of Al-5Zn-2Mg alloy and demonstrated that the softening at high temperature is associated with the grain coarsening during dynamic recovery process. Many researches about the 7000 series alloys show that the plastic forming of the Al-Cu-Mg-Zn strips should be conducted under high pressure at elevated temperature. However, the hot workability of 7075 alloy strips modified by TRC with electrical pulse field is barely investigated. Therefore, it is very important to study the influence of electrical pulse (EP) current on plastic deformation behavior of 7075 alloy strips at elevated temperature.

In this research, the 7075 alloy strips were modified by TRC with EP current, and their tensile behavior at high temperature was studied. Then, the constitutive relations and processing maps were established, providing a basis for further investigation of thermoplastic deformation and thermoforming of alloys.

1 Experiment

The 7075 alloy strips were prepared by TRC with and without EP current, namely EP-modified and original 7075 alloy strip, respectively. The specimens with excellent surface quality were prepared, as shown in Fig. 1. The nominal composition of the 7075 alloy strips is listed in Table 1.

The Al (99.85wt%) ingot and pure alloys agents (Zn, Mg, Cu) were melted with the theoretical proportion in a RJ 2-21-8 electrical resistance furnace at 800 °C for several hours until the mixture was completely dissolved. Then the dross was cleaned at 700~720 °C. Finally, the furnace temperature was reduced to 675 °C before TRC process. The technical parameters of TRC process are listed in Table 2. The EP current with

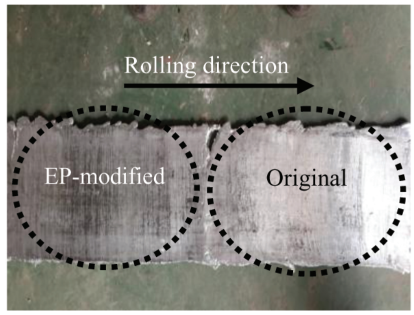

Fig.1 Appearance of EP-modified and original 7075 alloy strips

Table 1 Nominal composition of 7075 alloy strips (wt%)

Zn	Si	Mn	Mg	Fe	Cr	Cu	Al
5.80	0.43	0.35	2.85	0.55	0.22	1.85	Bal.

the single cycle of 0.005 s in duration and 300 A in intensity was introduced into the mushy region during continuous and stable TRC manufacturing followed by stress release treatment at 390 °C for 1.5 h and air cooling.

The isothermal tensile specimens under different forming conditions were obtained by the wire cutting machine along the rolling direction of the 7075 alloy strips. The tensile tests were conducted on the SHIMADZU AGX100KN instrument equipped with a resistance furnace with the temperature range of 250~400 °C. The specimens were placed inside the furnace at the designed temperature for 30 min. Then the tensile programs started with the strain rate of 0.001~0.01 s^{-1}.

When the specimen fractured, it was immediately taken out and quenched in cold water to preserve the microstructure at elevated temperatures.

The metallographic observation was conducted on a Leica DMI5000M optical microscope (OM) after the specimens were ground, polished, and acid-jetted in the mixed solution of 12.5vol% $HClO_4$ and 87.5vol% methanol electrolyte at room temperature for 3 s before rinsing by alcohol. The microstructure observations and energy dispersive spectroscopy (EDS) analysis were conducted on a S-3000 field-emission scanning electron microscope (SEM).

Then the specimens were ground along the normal direction (ND), and the electrolytic polishing with a solution of $HClO_4$ and C_2H_5OH with the volume ratio of 1:20 was performed at the voltage of 10 V for 10 s for electron back-scattered diffraction (EBSD) analysis by S-3000 EBSD testing system equipped with Oxford Instruments.

2 Results

2.1 Microstructure

Fig. 2 shows the typical OM images of EP-modified and original 7075 alloy strips. In the original region, the single-

Table 2 Parameters of TRC process with EP current

Roll diameter/mm	Roll gap/mm	TRC velocity/m·min^{-1}	Casting temperature/°C	EP frequency/Hz	Pulse width/s	Pulse peak current/A
500	5	0.9~1.2	670	20	0.005	300

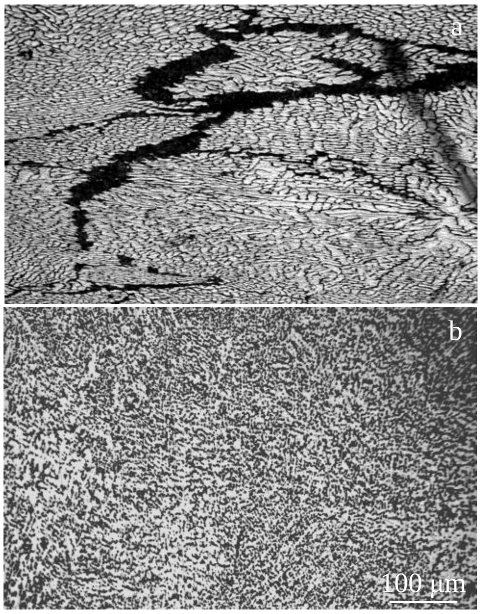

Fig.2 OM images of original (a) and EP-modified (b) 7075 alloy strips

path superheat emission from the center to surface of the liquid leads to the formation of coarse dendrites with difference sizes. Meanwhile, the structure shows crisscross shape with severe centerline segregation, consisting of precipitates with different thermophysical properties after dendrite overlapping. The uniform microstructure of EP-modified region consists of numerous fine and dense dendrite fragmentations, and no segregation occurs due to the improved atomic diffusion ability caused by the electro-magnetic induction of pulse current.

Fig. 3a shows the back scattered electron (BSE) image of the Al matrix and white bulk precipitates with the size of 10 μm. As shown in Fig.3b, the phase boundaries are fuzzed and the grains are refined. The network with irregular distribution is formed by the Al-Zn-Mg-Cu eutectic quaternary phase, as indicated in Fig. 3c. The Al matrix after EP-modified TRC process accounts for 51.799at%, which decreases by 7.506at% compared with that in the original specimen. Moreover, the improvement in diffusion ability of alloying elements (Mg, Cu, and Zn) leads to the increase in Mg and Cu contents in the EP-modified 7075 alloy strip by 1.974at% and 12.929at%, respectively, compared with those in the original 7075 alloy strip. However, the Zn content is reduced from 14.280at% to 6.883at% in 7075 alloy strips after EP-modified TRC process. As an external influence factor during solidification, EP current prolongs the duration of the liquid-solid transformation. Therefore, the Mg atoms are sufficiently diffused, while the Cu and Zn with relatively low diffusion ability undergo the competitive diffusion due to their similar atomic sizes. Based on Fig.3c and 3d, the Al and Zn contents in the precipitates of EP-modified 7075 alloy strips are decreased, while the Cu content is increased.

2.2 Thermomechanical properties

As shown in Fig. 4, the peak flow stress is consistently decreased with increasing the tensile temperature or decreasing the strain rate. The biggest deformation is obtained at the elevated temperature of 350 °C for both the original and EP-modified 7075 alloy strips. At high temperature, the dynamic recrystallization mainly promotes the strain softening, and even superplasticity can be achieved for the EP-modified 7075 alloy strips under the proper conditions of deformation temperature at 350 °C. The increased flow stress is induced by the high stirring and vibrating resulting from EP current. Besides, the diffusion of Zn, Mg, and, Cu is improved. The peak true stress under different deformation conditions is listed in Table 3.

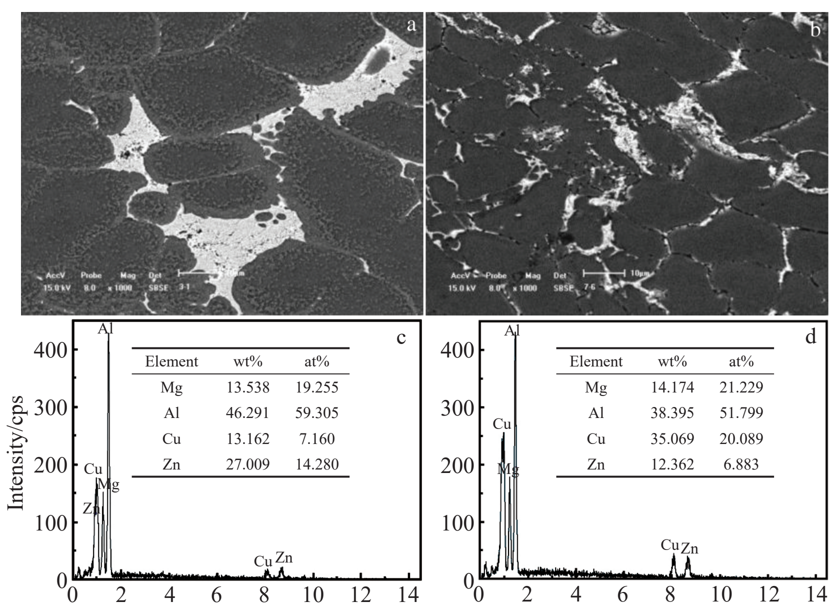

Fig.3 BSE images (a, b) and corresponding EDS analyses (c, d) of initial precipitates in original (a, c) and EP-modified (b, d) 7075 alloy strips

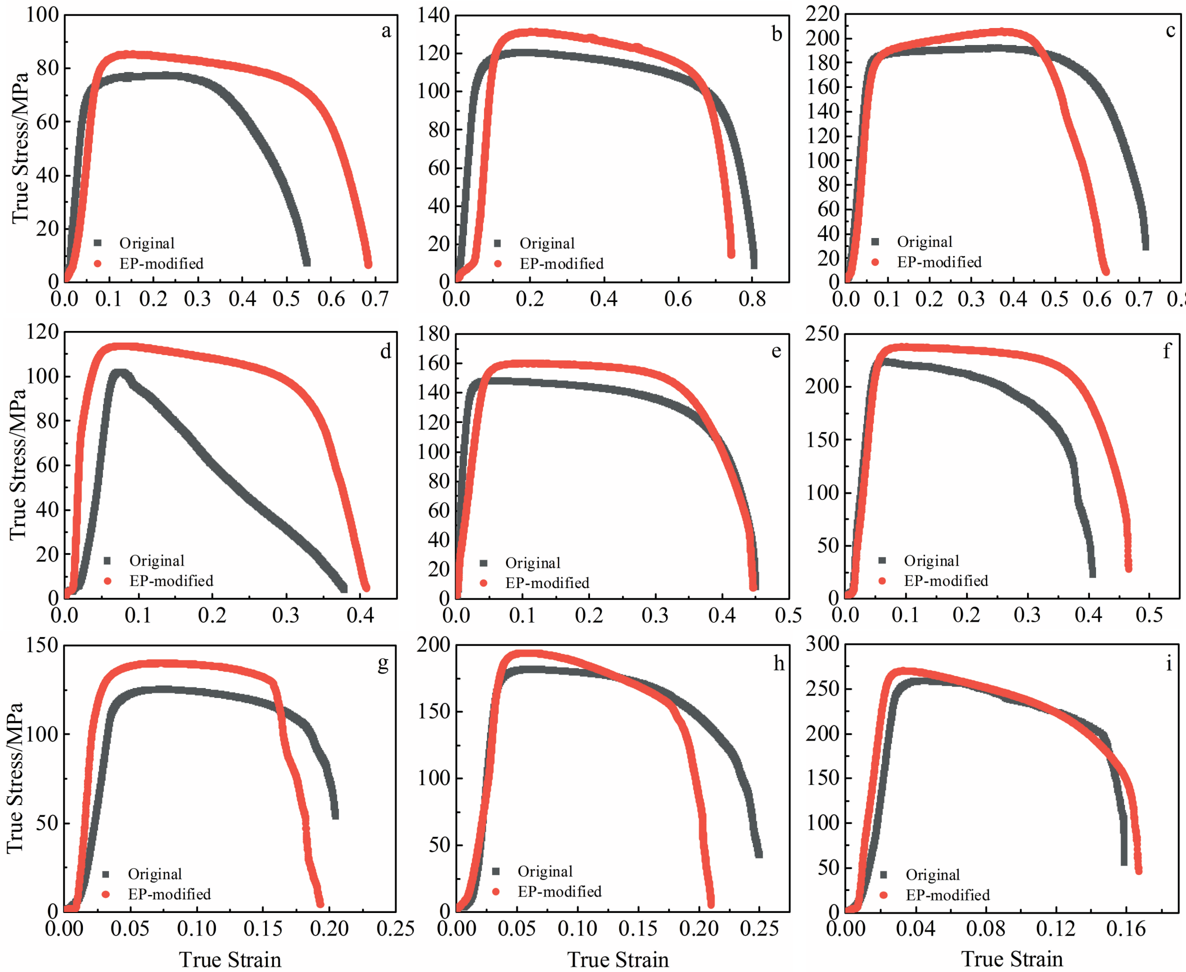

Fig.4 True stress-true strain curves of original and EP-modified 7075 alloy strips under different deformation conditions: (a)350 °C/0.001 s^{-1}; (b) 350 °C/0.005 s^{-1}; (c) 350 °C/0.01 s^{-1}; (d)300 °C/0.001 s^{-1}; (e) 300 °C/0.005 s^{-1}; (f) 300 °C/0.01 s^{-1}; (g) 250 °C/0.001 s^{-1}; (h) 250 °C/0.005 s^{-1}; (i) 250 °C/0.01 s^{-1}

Table 3 Peak true stress of original and EP-modified 7075 alloy strips under different deformation conditions (MPa)

Strain rate/s^{-1}	350 °C		300 °C		250 °C	
	Original	EP-modified	Original	EP-modified	Original	EP-modified
0.001	77.5	85.5	101.5	113.5	123.0	140.5
0.005	120.0	131.0	151.0	160.5	180.0	194.0
0.01	192.5	204.0	225.0	238.0	258.0	270.0

The peak stress of 7075 alloy strips is gradually increased with decreasing the tensile temperature or increasing the strain rate. The stress change trend with tensile temperature or strain rate is independent of the introduction of EP current in TRC process. The true stress at 250 °C of EP-modified 7075 alloy strips is 140.5, 194.0, and 270.0 MPa, which is about 1.1 times higher than that of original 7075 alloy strips at the strain rate of 0.001, 0.005, and 0.01 s^{-1}, respectively. Similar variation trends can be obtained at 300 and 350 °C: the stress of EP-modified 7075 alloy strips is generally slightly higher than that of original 7075 alloy strips.

2.3 Fracture

Fig. 5a and 5b show the fracture morphologies of original and EP-modified 7075 alloy strips, which indicates the typical ductile behavior characterized by obvious dimples of different sizes. It can be noted that the transgranular brittle fracture occurs at 250 °C and strain rate of 0.01 s^{-1} (Fig.5c and 5d)[15].

The dimples in fracture surface under high temperature and low strain are manifested as low-density pits of different forms and sizes. The tearing ridges are relatively sharp, as shown in Fig.5a. After EP-modified TRC process, the dimples with relatively smooth surface are formed through the liquid-like flow of the grain boundary sliding, as shown in Fig. 5b. With decreasing the temperature and increasing the deformation rate, the viscous flow of the grain boundary sliding is weakened and the cleavage fracture occurs[16], as

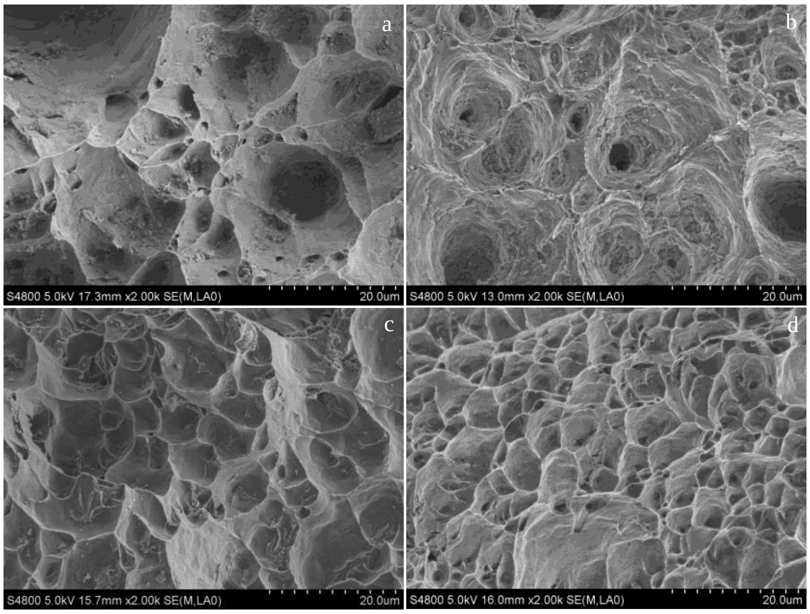

Fig.5 Fracture morphologies of original (a, c) and EP-modified (b, d) 7075 alloy strips under different deformation conditions: (a, b) 350 °C/0.001 s^{-1}; (c, d) 250 °C/0.01 s^{-1}

shown in Fig. 5c. According to Fig. 5d, the fracture morphology consists of tearing ridges and many small dimples, suggesting that the increasing ductility facilitates the typical quasi-cleavage fracture.

3 Discussion

3.1 Effect of EP current on microstructure

Fig. 6 shows the Euler images of specimens after heat treatment at 350 °C for 30 min before the hot tensile tests. It can be observed that the initial microstructure of EP-modified specimen still has the smaller grains than the original specimen does. Generally, the partial recrystallization may trigger the obvious change of the grain size from over 200 μm to below 100 μm. Besides, the rolling texture of face-centered cubic (fcc) 7075 alloy strips presents the {423}<144> orientation, as shown in Fig. 6a. While EP-modified 7075 alloy specimen shows the {421}<216> orientation. The microstructure and texture differences are related to the mechanical action of the erosion caused by EP current wind inside the semisolid mushy zone during TRC production.

The microstructure and texture characteristics after hot deformation are presented in Fig. 7. The EP-modified specimen shows a prominent rolling deformation texture at 350 °C under strain rate of 0.001 s^{-1} (Fig.7b), which is related to its elongated grain microstructure caused by the dynamic recrystallization. It should be noted that the elongation of over 100% has close association with the elongated and twisted grains until the recrystallization occurs.

It can also be observed that the original specimen has a weak and complex deformation texture, as shown in Fig. 7a. The dispersion poles can be observed, as a result of the reduction in specimen ductility (Fig.4a). Besides, the grains in the original specimens are elongated and twisted in the local

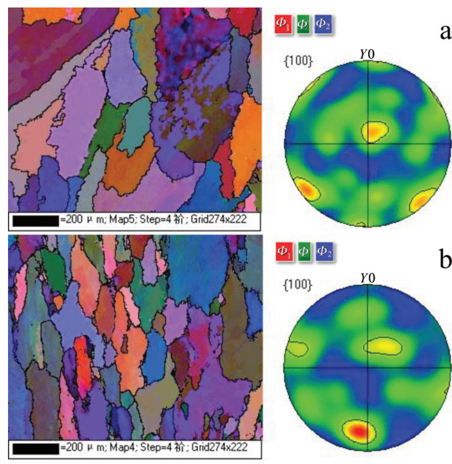

Fig.6 Euler images of heat-treated original (a) and EP-modified (b) 7075 alloy strips before hot deformation

recrystallization.

3.2 Effect of EP current on hot formability

3.2.1 Constitutive model

According to the true stress-true strain curves of original and EP-modified 7075 alloy strips (Fig. 4), the regular evolution of the true stress and true strain is suitable for the Zener-Hollomon constitutive model[17].

Under low strain, the steady flow stress is increased exponentially with increasing the strain rate due to the plastic deformation, as expressed by Eq.(1):

$$\dot{\varepsilon} = A_1\sigma^{n_1} \tag{1}$$

where A_1 and n_1 are the material constants independent of the testing temperature; σ is the stress.

Meanwhile, under high stress, the relation between the peak flow stress σ_p and the strain rate $\dot{\varepsilon}$ is expressed by Eq.(2)[18], as

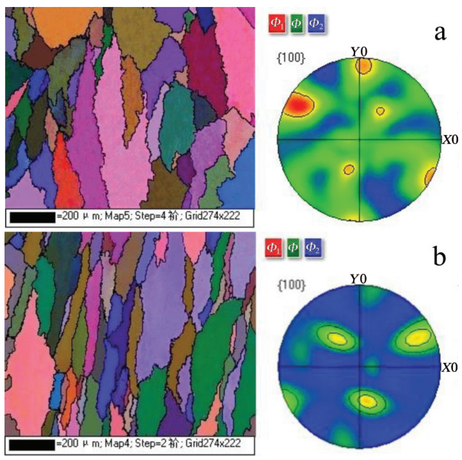

Fig.7 Euler images of near-fraction region in original (a) and EP-modified (b) 7075 alloy strips after hot deformation

follows:

$$\dot{\varepsilon} = A_2\exp(\beta\sigma) \tag{2}$$

where A_2 and β are the material constants independent of the testing temperature, and deformation condition $\alpha=\beta/n_1$. For the original 7075 alloy strips, β and n_1 are set as 0.02 and 3.0 according to the average values of the reciprocal of the slope of fitting line of $\ln\dot{\varepsilon}$-σ_p and $\ln\dot{\varepsilon}$-$\ln\sigma_p$, respectively. For the EP-modified 7075 alloy strips, β and n_1 are considered as 0.02 and 3.3, respectively. Therefore, α is determined as 6.67×10^{-3} and 6.12×10^{-3} for the original and EP-modified 7075 alloy strips, respectively.

The hyperbolic sine equation containing the deformation activation energy Q and the deformation temperature T established by Senars and Tegart is suitable for description of the mechanical properties of materials prepared by specific process under flow stress at elevated temperatures. The equation for high temperature tensile tests is expressed by Eq.(3), as follows:

$$\dot{\varepsilon} = A\left[\sinh(\alpha\sigma_p)\right]^n\exp\left(-Q/RT\right) \tag{3}$$

where A and n are material constants; R is the universal gas constant of 8.314 $J\cdot mol^{-1}\cdot K^{-1}$. Then the Zener-Hollomon model can be presented as follows[19]:

$$Z = \dot{\varepsilon}\exp\left(Q/RT\right) = A\left[\sinh(\alpha\sigma)\right]^n \tag{4}$$

where Z is related to the deformation condition α.

In this research, the deformation activation energy Q is proportional to $\left.\frac{\partial\ln\dot{\varepsilon}}{\partial\ln[\sinh(\alpha\sigma)]}\right|_T \left.\frac{\partial\ln[\sinh(\alpha\sigma)]}{\partial(1/T)}\right|_{\dot{\varepsilon}}$, and the scale factor is the universal gas constant R.

Therefore, the deformation activation energy of original and EP-modified 7075 Al strips is calculated as 111.4 and 134.9 kJ/mol, respectively. Thus, the existence of EP current inside the mushy liquid during rapid solidification can effectively increase the deformation activation energy of aluminum alloys. Finally, the parameter Z of Zener-Hollomon model in TRC and EP-modified TRC processes can be calculated by Eq. (4), and the constitutive models are represented as follows:

$$\begin{aligned}\dot{\varepsilon}_{\mathrm{original}} &= 3.353\times10^7\left[\sinh\left(7.48\times10^{-3}\sigma_{\mathrm{original}}\right)\right]^{6.28}\exp\left(-\frac{1.114\times10^5}{RT}\right)\\ \dot{\varepsilon}_{\mathrm{EP-modified}} &= 4.635\times10^9\left[\sinh\left(6.52\times10^{-3}\sigma_{\mathrm{EP-modified}}\right)\right]^{6.90}\exp\left(-\frac{1.349\times10^5}{RT}\right)\end{aligned} \tag{5}$$

The value of $\ln A$ is the y-intercept of the $\ln Z$-$\ln[\sinh(\alpha\sigma)]$ curve, as shown in Fig. 8. The comparison result of constitutive models between original and EP-modified alloy strips aims to make further elucidation of the advantages of electro-magnetic technology in metallic plastic forming, and to establish the quantitative evaluation of constitutive models.

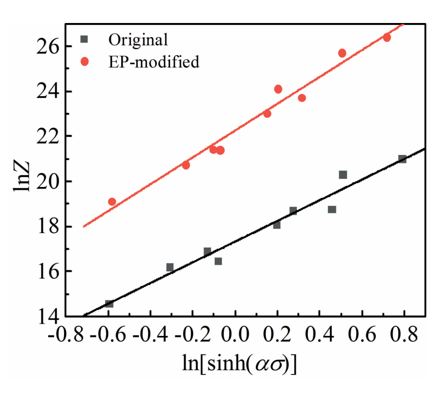

Fig.8 $\ln Z$-$\ln[\sinh(\alpha\sigma)]$ curves of original and EP-modified 7075 alloy strips

3.2.2 Processing map

The processing map, based on the organic combination of the dynamic materials model (DMM) and Prasad instability criterion, is used to predict the plastic deformation within the stable region. The model function with processing parameters can be expressed as follows:

$$m = \partial(\ln\sigma)/\partial(\ln\dot{\varepsilon}) \tag{6}$$

where m is the strain rate sensitivity (for ideal viscous flow state, m=1). The energy dissipation J during microstructure transformation reaches the maximum value, and then the dissipation efficiency η and the instability flow criterion $\xi(\dot{\varepsilon})$ are expressed as follows:

$$\begin{aligned}\eta &= \frac{J}{J_{\max}} = \frac{2m}{1+m}\\ \xi(\dot{\varepsilon}) &= \frac{\partial\ln(\eta/2)}{\partial\ln(\dot{\varepsilon})} + m < 0\end{aligned} \tag{7}$$

The processing maps at strain of 0.1 and 0.2 of original and EP-modified 7075 alloy strips are shown in Fig. 9. The gray instability regions are always accompanied with the plastic flow localization and microcracks. Gradually, the deformation conditions outside the instability regions are suitable for the

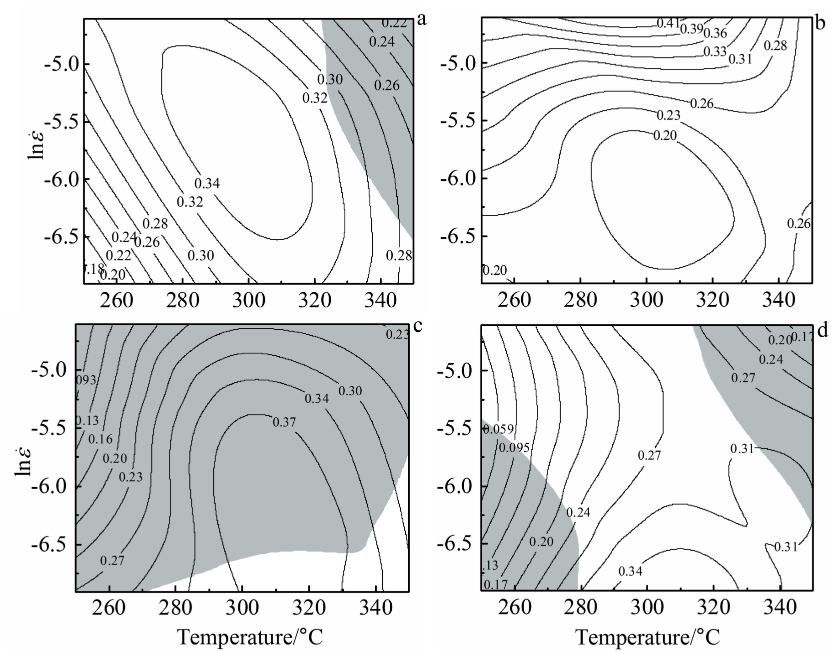

Fig.9 Processing maps of original (a, c) and EP-modified (b, d) 7075 alloy strips at strain of 0.1 (a, b) and 0.2 (c, d)

processing. Furthermore, the higher the energy dissipation efficiency, the better the thermal formability of the materials. The thermal formability of 7075 alloys is enhanced by EP-modified TRC processing through selecting higher dissipation efficiency inside the safe region ($\xi(\dot{\varepsilon})$ >0). Without EP modification, the peak η outside the instability regions is close to 0.34 at the low strain of 0.1 under the deformation conditions of temperature of 290~310 °C and strain rate of 0.002~0.004 s^{-1}. With EP current, the alloy ductility is improved and the processing strain is enhanced (ε=0.2). The suitable deformation conditions are temperature of 290~330 °C and strain rate of 0.001~0.002 s^{-1}.

Without EP current, the continuous safe production is very sensitive to the deformation, i. e., after applying a slightly larger deformation, the processing map is almost entirely covered by the instability region (marked by grey), as shown in Fig.9c. When the solidification process is improved by EP current, the unsafe area is dispersed and the contour lines outside the gray zones are not relatively dense, which provides a wide and continuous range of hot working. In contrast, the thermal formability of 7075 alloys is enhanced by introduction of EP current.

4 Conclusions

1) When the electrical pulse (EP) current is introduced into the twin-roll casting (TRC) process, the microstructure of the 7075 alloy strips is composed of numerous fine and uniform dendrites without segregation. Meanwhile the second phase shows are fuzzed boundary and is refined with dispersed distribution.

2) The elongation over 100% can be obtained at the deformation temperature of 350 °C under strain rate of 0.001 s^{-1}. The peak stress of EP-modified 7075 alloy strips is about 1.1 times higher than that of original 7075 alloy strips. Therefore, the TRC process with EP current improves the alloy ductility.

3) The fracture surface consists of many dimples with different forms and sizes at high temperature of 350 °C. While at 250 °C, the brittle behavior characterized by the cleavage fracture and quasi-cleavage fracture can be observed. The obvious characteristic of viscous flow due to grain boundary sliding occurs in the EP-modified strips.

4) The hyperbolic sine relationship between the flow stress and strain rate can be expressed by Zener-Holloman constitution model for original 7075 alloy strips: $\dot{\varepsilon}_{\text{original}} = 3.353 \times 10^7\left[\sinh\left(7.48 \times 10^{-3}\sigma_{\text{original}}\right)\right]^{6.28}\exp\left(-\dfrac{1.114 \times 10^5}{RT}\right)$. The deformation activation energy Q and Zener-Holloman parameter ln$Z$ are 111.4 kJ/mol and 17.3, respectively. The flow stress of EP-modified strip can be expressed as $\dot{\varepsilon}_{\text{EP - modified}} = 4.635 \times 10^9\left[\sinh\left(6.52 \times 10^{-3}\sigma_{\text{EP - modified}}\right)\right]^{6.90}\exp\left(-\dfrac{1.349 \times 10^5}{RT}\right)$. The deformation activation energy Q and the Zener-Holloman parameter ln$Z$ are 134.9 kJ/mol and 22.3, respectively.

5) The thermal formability of 7075 alloys is enhanced by EP-modified TRC processing. The suitable hot working parameters are the temperature of 290~330 °C and strain rate of 0.001~0.002 s^{-1}.

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脉冲电场下的7075双辊铸轧板热变形行为

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摘　要：在变形温度250~350 ℃和应变速率0.001~0.01 s^{-1}的条件下进行热拉伸试验，研究了厚度为5 mm的7075合金传统铸轧板和电脉冲铸轧板的微观组织和热成形性能。实验用脉冲电流参数为：单周期脉宽0.005 s和峰值强度300 A。结果显示，脉冲电流能够促进凝固过程的枝晶细化，并诱发组织均匀化。由于电磁振荡增强了凝固过程中溶质混合能力，极压电流有效地促进了晶粒细化和析出相的均匀化。同时，面心立方（fcc）铝合金铸轧板织构具有{423}<144>取向，经脉冲电流改性后，取向为{421}<216>。脉冲电流处理后的合金峰值流动应力约为未处理合金的1.1~1.3倍。电子背散射衍射分析表明，脉冲电流通过促进动态再结晶的方式，有效地改善了晶粒的择优分布。在此基础上，分别建立了铝合金带材的双曲正弦方程和含Zener-Holloman参数的本构模型。此外，通过对断口形貌的观察发现，脉冲电流的引入有利于提高7075铝合金的高温机械性能。最后建立了优化的工艺流程图，并确定了适宜的热加工温度为290~330 ℃和应变速率为0.001~0.002 s^{-1}。

关键词：铝合金；双辊铸轧；脉冲电场；高温变形；热成形性

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