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ARTICLE

Effect of Ti Addition on Microstructures and Crack Behavior of Twin-Roll Cast-Rolled 7050 Alloy Plate

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Abstract: The influence and mechanism of Ti addition on the crack formation of twin-roll cast-rolled plates of 7050 aluminum alloys (TRC-7050) were studied with field-emission scanning electron microscopy (FESEM), differential scanning calorimetry (DSC), and X-ray diffraction (XRD). The results show that Ti addition can significantly refine the grain sizes of the twin-roll casting plate, change the grain growth modes, improve the fluidity of the alloy, make the cast-rolled structure denser, eliminate the local stress concentration in the alloy, and inhibit the occurrence of casting cracks. Appropriate amount of Ti addition can reduce the solid-liquid phase interval of the TRC-7050, reduce the temperature gradient of the nucleation solidification front and effectively inhibit the segregation of components, thereby reducing the number of low-melting compounds at the grain boundary and generation of coarse second phases, and then enhancing the resistance to the thermal cracking of the TRC-7050. 0.2 wt% Ti has the best inhibitory effect on the formation of TRC-7050 cracks. However, excess Ti addition will aggregate and form a sheet-like Ti-containing brittle phase, which will subsequently destroy the compactness of the structure and promote the initiation of cracks.

Key words: aluminum alloys; twin-roll casting; microstructures; crack

TRC-7050 has the merits of low density, high specific strength and toughness, and is extensively used for producing precision parts such as auto parts and electronics[1,2]. Compared with the traditional process, the twin-roll casting technique has several advantages such as short process and low consumption of power and time[3,4]. However, there are considerable composition segregations and columnar dendrites in the TRC-7050 with complicated composition[5-7]. The average size of the grains is too large and unevenly distributed in the TRC-7050. Cracks can be formed quite easily in the TRC-7050, which seriously restrict the application in the industry[8,9]. Therefore, it is extremely important to suppress the formation of cracks in the TRC-7050. Cao et al[10] reported that reducing the temperature gradient before the solidification of the crystal nucleus can reduce the component supercooling caused by solute enrichment to inhibit the generation of macroscopic and microscopic segregation, and to reduce the number of eutectic compounds with low melting point at grain boundary to decrease the crack tendency in the TRC-7050. In addition, several studies have reported that the use of master alloy as refiners can effectively suppress crack formation in aluminum alloys. Al-Ti alloy is an useful refiner, and Ti exists in the Al-Ti alloy as dense Al_3Ti phases[11,12]. Li et al[13] developed a nano-TiN/Ti composite grain refiner, which uses Al_3Ti to refine second phase composed of σ[Mg(Zn, Cu, Al)$_2$], $\theta(Al_2Cu)$ and iron-containing impurity phase Al_7Cu_2Fe in the Al-Zn-Mg-Cu alloys for reducing the eutectic region, thereby reducing the generation of crack sources in the aluminum alloy. Zhao et al[14] found that the Al_3Ti phase in Al-4Ti master alloy changes from petal-like morphology to blocky morphology when the cooling rate decreases and finally grows into an elongated sheet shape. The Al-4Ti alloy with bulk Al_3Ti particles has the best grain refining efficiency and the cracking effect is the strongest, which has the strongest inhibitory effect on cracks. The above studies have shown that adding a Ti-containing refiner can improve the component

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segregation of the plate, reduce the low melting eutectic phase and columnar dendrites, refine the grains, thereby reducing the tendency to crack. However, the influence of amounts of Ti addition on the crack of the TRC-7050 has been seldom studied. In the present work, the influence and mechanism of amounts of Ti addition on the cracking of TRC-7050 were studied.

1 Experiment

First, the rust from the tool in direct contact with the melt was removed, and then the 7050 aluminum alloys were smelted at 740~750 °C. Subsequently, the weighed $AlTi_{10}$ master alloy was added and stirred well with graphite carbon rods. After standing for a while, when the temperature was lowered to 690 °C, the molten metal was poured out and rolled in a two-roll mill. The rolling speed and rolling gap were controlled by a computer controlled cabinet with a rolling speed of 14 m/min and the rolled sheet thickness was 4 mm. The actual composition of 7050 aluminum alloys used in the experiment was tested by a direct reading spectrometer, as shown in Table 1. Four types of Ti microalloyed 7050 alloys were designed, as shown in Table 2.

The length of the cast-rolled plate sample used in this experiment was taken along the rolling direction with the cross-sectional dimension of 10 mm×12 mm. The optical metallographic sample was mechanically polished and then subjected to anode coating (the coating reagent of 38 mL H_2SO_4+43 mL H_3PO_4+19 mL H_2O, voltage of 25 V, time of 150 s), and then the metallographic structure was observed by a microscope. The radial distribution, secondary phase morphology, and the composition of the solute were analyzed by the SIGMA HD field emission high-resolution scanning electron microscope (FESEM) combined with energy-dispersive spectrometer (EDS). The dendrite spacing was measured by a straight cross-section method. The sample was subjected to thermal analysis using a differential thermal analyzer (DSC) at a heating rate of 10 °C/min, and the DSC curve was obtained by Origin. XRD analysis of the surface of the sheet was performed by an X'Pert Powder type X-ray diffractometer, and the diffraction angle range was 10°~90° with a detection time of 30 min. Statistical analysis of fine grains in metallographic structures was performed by the software of Image Pro Plus 6.0.

Table 1 Chemical composition of 7050 aluminum alloy (wt%)

Zn	Mg	Cu	Cr	Zr	Fe	Si	Ti	Al
6.37	1.61	1.69	<0.01	0.09	0.03	0.01	0.04	Bal.

Table 2 Chemical composition of designed aluminum alloys (wt%)

Alloy	Zn	Mg	Cu	Ti	Al
1#	6.37	1.61	1.69	0	Bal.
2#	6.37	1.61	1.69	0.1	Bal.
3#	6.37	1.61	1.69	0.2	Bal.
4#	6.37	1.61	1.69	0.3	Bal.

2 Results and Discussion

To quantitatively calculate the surface cracks of cast-rolled sheets with different Ti contents, the crack index is defined as the crack length per unit area of the cast-rolled sheet in units of m^{-1}. The calculation formula is as follows:

$$\text{Crack index} = \sum L_{\text{crack}}/S \quad (1)$$

The statistical results in Fig.1 show that the number of cracks in the cast-rolled plate decreases with increase in Ti content. When the Ti content reaches 0.2 wt%, the crack index is the least (~0.43 m^{-1}), and the number of cracks in the plate is the least at this condition. However, the crack index increases when the Ti content increases to 0.3 wt%.

2.1 Solidification structure of Ti 7050 cast-rolled plate

Fig.2 shows the polarized metallographic structure of the core portion of the 7050 cast-rolled plate with different Ti contents after electrolytic polishing and anode coating. The figure shows that the grain of the alloy without Ti addition is obviously dendritic, and a large number of non-equilibrium eutectic phases are distributed around the grain boundary. The grain size of the edge is ~63.5 μm, and the grain size of the core is ~53.4 μm. Such a phenomenon of non-uniform grains will cause stress concentration during the cooling process of the cast-rolled plate, and it is easy to induce cracks. With the addition of Ti in the alloy, the grains are remarkably refined, and the columnar dendrites in the structure gradually evolve into equiaxed crystals, and the distribution is more uniform. Because the primary α-Al phase is refined, the non-equilibrium liquid phase between the dendrites is dispersed, and the non-equilibrium eutectic structure is refined, which effectively reduces the degree of dendrite segregation. When the Ti content is 0.2 wt%, the grain size is the least (~26.7 μm). When the Ti content is 0.3 wt%, the grain size is ~31.8 μm. When the Ti content exceeds 0.2 wt%, the grain size is not further refined but increases, causing the crack tendency to intensify[15].

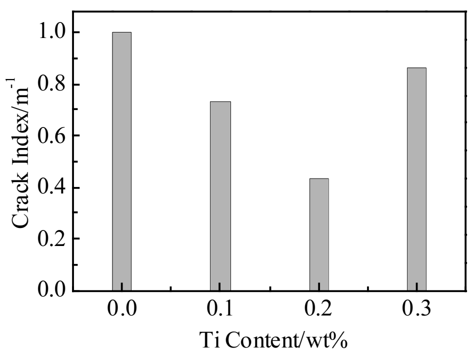

Fig.1 Crack index of 7050 cast-rolled plate with different Ti contents

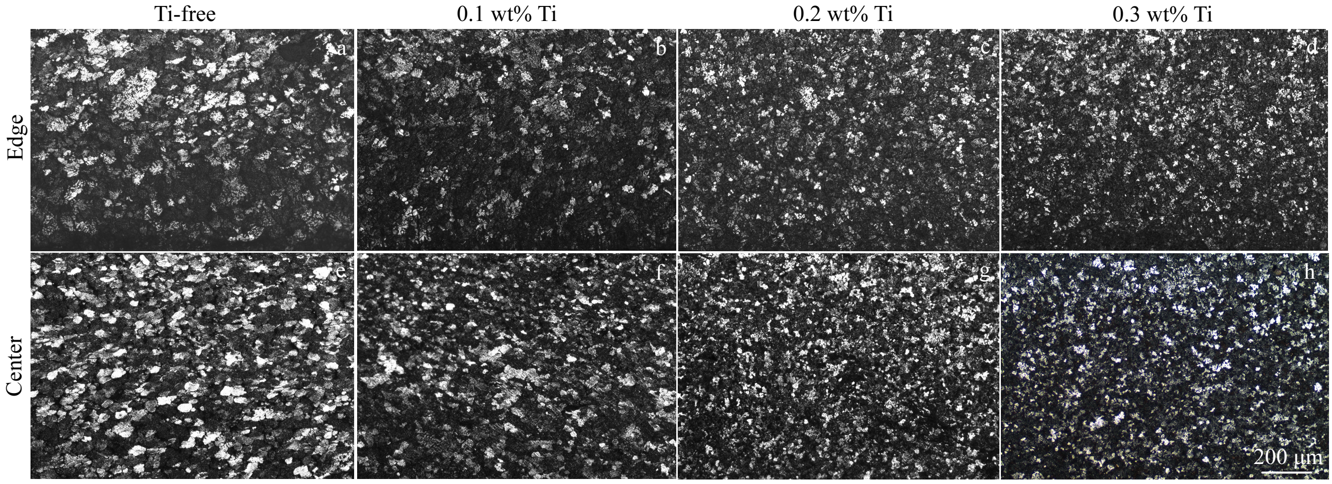

Fig.2 Microstructures of 7050 cast-rolled plate with different Ti contents

Fig.3 shows the SEM images of the solidification precipitates in the solidified structure of the TRC-7050. The white region is a coarse eutectic structure formed by non-equilibrium solidification. Fig.3a shows that the unbalanced eutectic structure at the grain boundary of the alloy is mostly a mesh phase. With reference to the literature and the use of energy spectrum, it can be inferred that this network layer phase is AlZnMgCu phase[16]. Certain coarse eutectic phases are composed of two or more phases, not only just a single phase of AlZnMgCu. Fig.3b shows that the coarse second phase is composed of a long strip-like Fe-rich phase of Al_7Cu_2Fe, a mesh-like phase of AlZnMgCu, and a point-like phase of Al_3Zr[17].

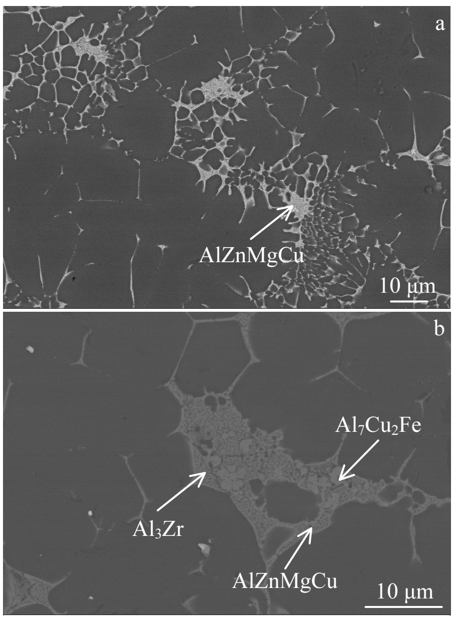

Fig.3 SEM images of solidified precipitates in 7050 aluminum alloy cast-rolled plate: (a) AlZnMgCu; (b) Al_3Zr, AlZnMgCu and Al_7Cu_2Fe

EDS can be used to detect the distribution of each element in different second phases. To clearly observe the distribution and segregation of each element in the matrix and the second phase, we performed elemental surface scanning analysis on the TRC-7050. Fig.4 displays that the primary alloying elements, such as Zn, Cu and Mg, show obvious enrichment phenomena at the grain boundary eutectic structure and second phase. However, there are also significant differences in the degree of enrichment segregation of each element. The matrix element Al has the greatest compositional fluctuation at the grains and boundaries. Furthermore, significant segregation of Cu and Zn is observed among the primary alloying elements.

2.2 Al_3Ti morphology in TRC-7050 with Ti

Nikitin et al[18] studied the refinement effect of different Al_3Ti on the morphology of Al-Ti alloys. The results show that the size and shape of Al_3Ti phase in Al-Ti alloy can affect the refining effect of the alloy obviously, and the refinement effect of bulk Al_3Ti phase is the best. Fig.5 shows the SEM results and EDS analysis of the second phase for the microstructure of the TRC-7050 with Ti. When the Ti content is 0.1 wt%, a small amount of spherical phase (A in Fig.5a) exists in the crystal grains. EDS analysis shows that the region has both Al and Ti elements, and the atomic ratio of Al:Ti is 3:1. Therefore, it can be inferred that the spherical phase is an Al_3Ti phase. When the Ti content is 0.2 wt%, the Al_3Ti phase in the microstructure is primarily in the form of small blocks (B in Fig.5b). However, a significant number of Al_3Ti particles are evenly distributed on the Al matrix, and the heterogeneous nucleation core of the alloy increases, further promoting the grain refinement. When the Ti content is 0.3 wt%, the morphology of Al_3Ti is in the form of sheets (C in Fig.5c), and the size>100 μm. The plate-like Al_3Ti is a hard and brittle

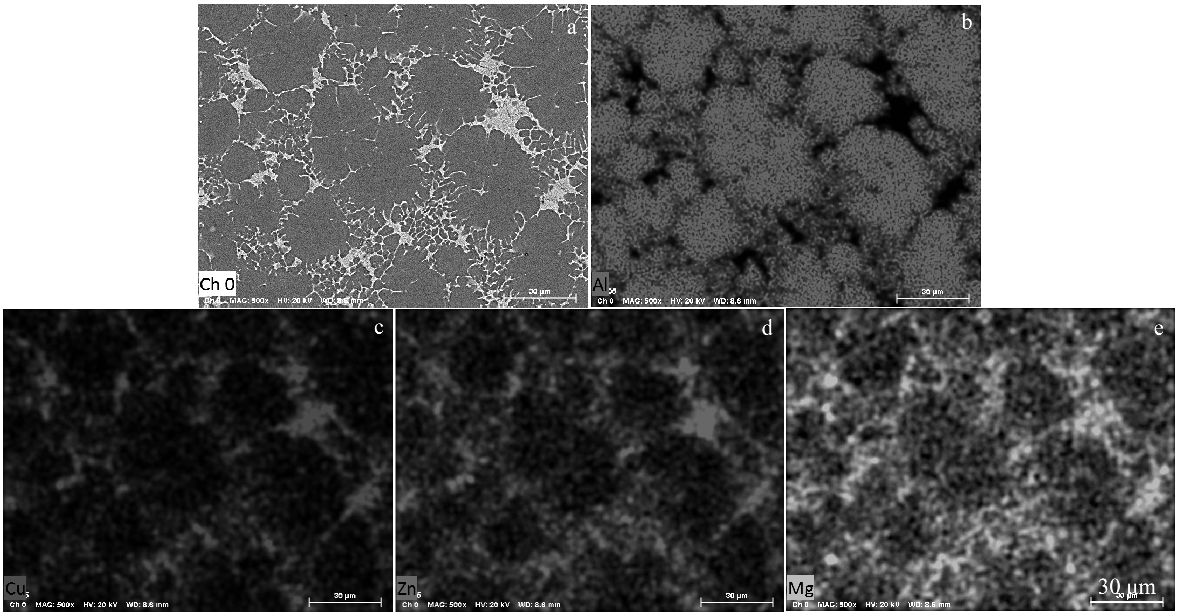

Fig.4 Microstructure (a) and EPMA images of solidified structure of 7050 cast-rolled plate: (b) Al, (c) Cu, (d) Zn, and (e) Mg

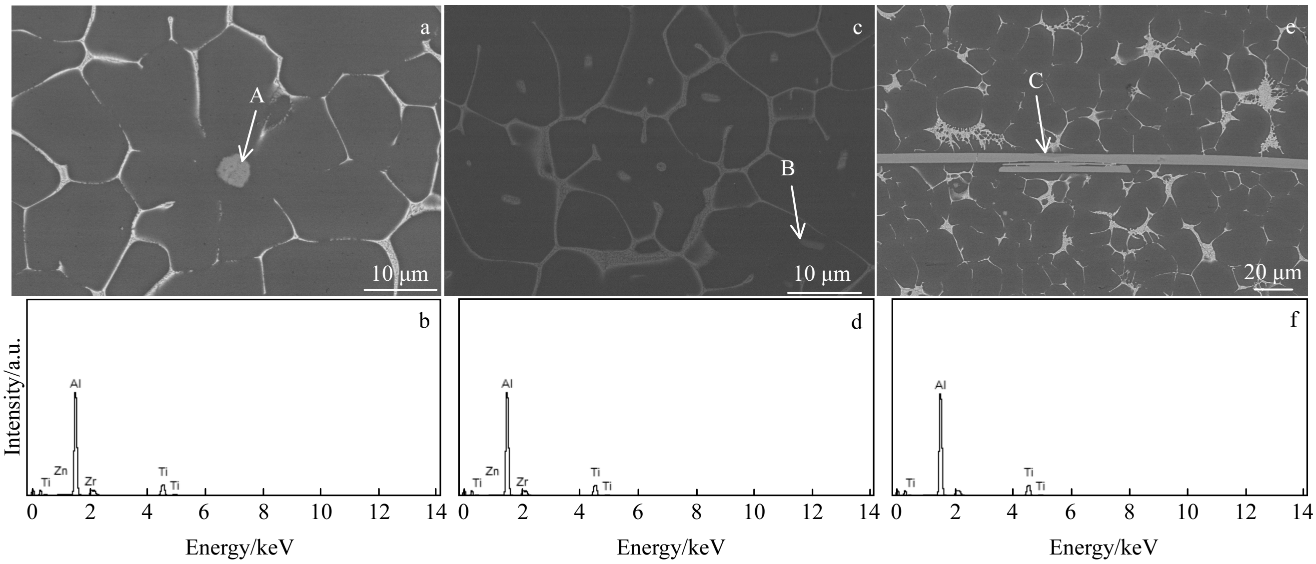

Fig.5 SEM images (a, c, e) and EDS spectra (b, d, f) of the second phase Al_3Ti of 7050 cast-rolled plate with different Ti contents: (a, b) 0.1 wt%, (c, d) 0.2 wt%, and (e, f) 0.3 wt%

phase with a large size that usually penetrates through several grains. It is unevenly distributed within the aluminum alloy, which weakens the refining effect of Ti considerably and forms a crack source.

2.3 Supercooling degree of TRC-7050 with Ti

Fig.6 shows the DSC curves for TRC-7050 with different Ti contents. It can be seen that there are two distinct endothermic peaks on the DSC melting curve of 7050 aluminum alloy with different Ti contents, and the liquidus temperature remains basically unchanged at ~638 °C. The endothermic peak at 472.76 °C of the sample without Ti element corresponds to the melting point of the low-melting point eutectic phase in the cast-rolled aluminum alloy structure, whereas the endothermic peak at 637.61 °C corresponds to the melting point of the α-Al matrix in the alloy. It is known that Ti has a considerable influence on the solidus temperature of 7050 alloy. It significantly shortens the solid-liquid two-phase interval of the alloy, increases the solidus temperature, and causes the alloy

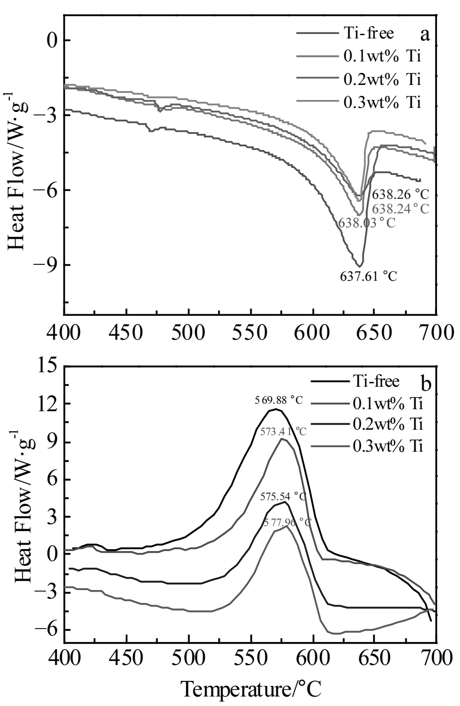

Fig.6 DSC curves of 7050 cast-rolled plate with different Ti contents: (a) liquidus temperature curves and (b) solidus temperature curves

melt to solidify in advance.

The exothermic onset temperature is the aluminum alloy melt nucleation starting temperature (T_n). The nucleation starts when $\Delta T > \Delta T_n$: $\Delta T_n = T_{eq} - T_n$ (ΔT_n is the melt nucleus supercooling)[19]. The calculations confirm that the degree of supercooling of the melt nucleus decreases with the increase of Ti content, while the nucleation supercooling decreases when the Ti content is 0.2 wt%, followed by additional decrease with increase of Ti content. Thus, the results confirm that Ti addition can reduce the degree of supercooling required for nucleating the melt, and the decrease of the degree of supercooling can cause the difference in the solid-liquid free energy required for the phase transformation of the alloy to decrease. The overall number of nucleation will reach a saturation[20]. Therefore, when the 7050 aluminum alloy sheet is casted and rolled with the Ti addition of 0.2 wt%, the melt nucleus is in a saturated state and the addition of the Ti element cannot further improve the refining effect. The Ti addition amount is preferably at 0.2 wt%.

2.4 Dendritic segregation in TRC-7050 with Ti

The metallographic micrograph and Image Tool software were used to measure the secondary dendrite arm spacing *S* of TRC-7050 with different contents of Ti. Fig.7 shows a plot of secondary dendrite arm spacing versus Ti content. The figure shows that the distance between the secondary dendrite arms decreases first and then increases with increasing the content

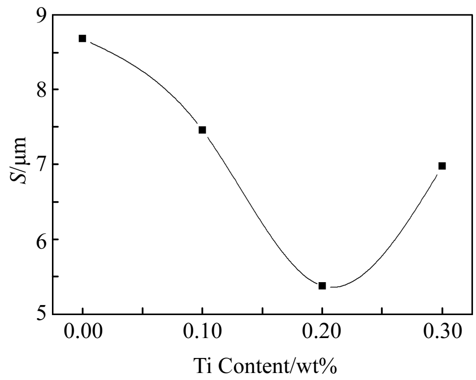

Fig.7 Relationship between secondary dendrite arm spacing (*S*) and Ti content of 7050 cast-rolled aluminum alloy

of Ti. This phenomenon can be understood by the Ti enrichment in the liquid phase of the dendrite front in the primary dendrite axis growth of the alloy. Ti enrichment changes the composition of the liquid phase around the dendrite axis, improves the solid solubility of other alloying elements, increases the component supercooling in the liquid around the primary dendrite axis, makes the secondary dendrites growing on the primary dendrite axis more likely to extend into the liquid phase, and then reduces the secondary dendrite arm spacing[21,22]. The secondary dendrite arm spacing is then increased because the solubility of solid Ti reaches saturation, the excess Ti forms a coarse second phase, the crystal grains are not refined, the alloying elements around the dendrites cannot be converted into other forms, and excessive Ti cannot promote the reduction of alloying elements around the dendrites. The proper addition of Ti can reduce the secondary dendrite spacing and decrease the diffusion distance of alloying elements, which are beneficial for the uniform distribution of alloying elements in the matrix, thereby increasing the solubility of alloying elements in the dendrites and refining the alloy. The segregation degree of elements between dendrites reduces the tendency of cracks in the cast-rolled aluminum alloys[23].

The dendritic segregation of TRC-7050 with different contents of Ti was measured, and three points were measured on the dendrite axis, the dendrites and the dendrite axis, and the alloy elements such as Al, Zn, Mg, Cu, Si, and Fe were measured by SEM (Fig.8). Fig.9 shows the change in the content of alloying elements on the shaft. The analysis shows that there are different degrees of dendrite segregation in the TRC-7050 with different contents of Ti. In all the cast-rolled samples, the content of Zn, Cu, Mg, and Fe in the dendrites is higher than that in the dendrite axis. The Si content in the dendrites is lower than that on the dendrite axis.

The degree of dendritic segregation of an element is determined by calculating the segregation ratio (SR). The calculation formula is as follows:

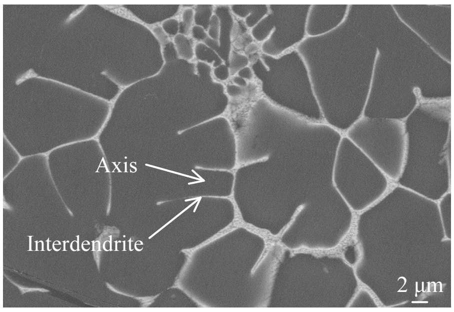

Fig.8 Crystal segregation measurement points of 7050 cast-rolled aluminum alloy

$$SR=C_{ID}/C_{DC} \quad (2)$$

where C_{ID} and C_{DC} refer to the alloying element concentration between the interdendritic and dendritic axes, respectively. When SR>1, the element segregation is normal, and the segregation is between the dendrites. The larger the SR, the more severe the segregation. When SR<1, the element is negatively segregated and the segregation is on the dendritic axis. The smaller the SR, the more severe the segregation. Furthermore, when SR=1, there is no microsegregation[24]. Table 3 shows the segregation ratio of alloying elements of TRC-7050 with different contents of Ti. The results show that as the Ti content increases, the degree of segregation of elements such as Zn, Mg, Cu, Fe, and Si gradually decreases,

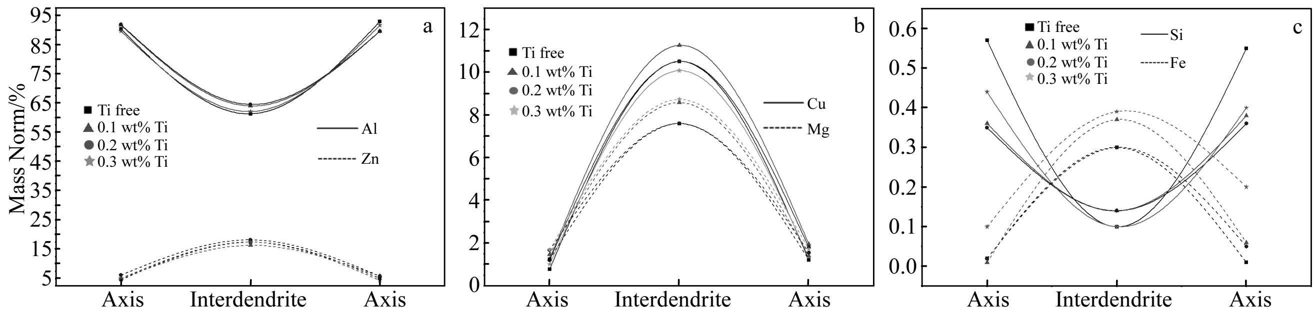

Fig.9 Variation of the content of alloying elements on the dendrites in cast-rolled sheets with different Ti contents: (a) Al, Zn, (b) Cu, Mg, and (c) Fe, Si

i.e., an appropriate amount of Ti can reduce the segregation of low melting point elements between dendrites. When the Ti content reaches 0.3 wt%, the degree of elemental segregation begins to increase because when the alloy contains a trace amount of Ti, it combines with Al to form a finely dispersed Al_3Ti phase, which can significantly promote grain refinement, greatly increase the number of grain boundaries, and decrease the content of alloying elements on the unit grain boundary. The content of alloying element in unit grain boundary is obviously reduced, which will increase the solubility of the alloying element in the matrix, and improve the dendrite segregation caused by composition segregation. However, when the Ti content in the alloy is considerably large, a coarse, hard and brittle phase Al_3Ti begins to appear in the structure, which in turn causes the grain refining effect to weaken.

Table 3 Segregation ratio of alloying elements on dendrite in 7050 cast-rolled plate with different Ti contents

Ti Content/ wt%	Al	Zn	Mg	Cu	Si	Fe
0	0.68	3.73	6.08	13.50	0.18	39.00
0.1	0.70	3.19	4.77	8.94	0.39	30.00
0.2	0.71	2.91	4.55	8.69	0.40	15.00
0.3	0.69	3.44	5.17	9.98	0.23	37.00

Therefore, the component segregation is not effectively improved, and the effect of dendritic segregation improvement is decreased.

2.5 Crack formation mechanism

The influence of trace amounts of Ti on the crack formation of TRC-7050 was examined under the same process parameters. As shown in Fig.10, the cast-rolled plate without Ti has transverse cracks at both the side portion and the core portion. The literature shows that in the cast-rolled production process, the 7050 aluminum alloy has the relatively wide solidification temperature range, and the heat transfer coefficient of the casting roll is higher[25,26]. When the alloy liquid comes in contact with the casting roll, the supercooling degree of the upper and lower surfaces of the blank is large. With larger and faster cooling, the equilibrium crystallization conditions are destroyed. The diffusion capacity of Zn, Mg and Cu in the solid solution is reduced, and the enrichment zone of the element is formed. Furthermore, unbalanced eutectic structure and other metastable phases begin to appear in the structure, which lead to the existence of the surface layer of the longitudinal section of the cast-rolled plate. This will lead to a large number of columnar dendrites in the cast-rolled plate, causing severe intracrystalline segregation[27]. The adhesion between these coarse eutectic phases and the

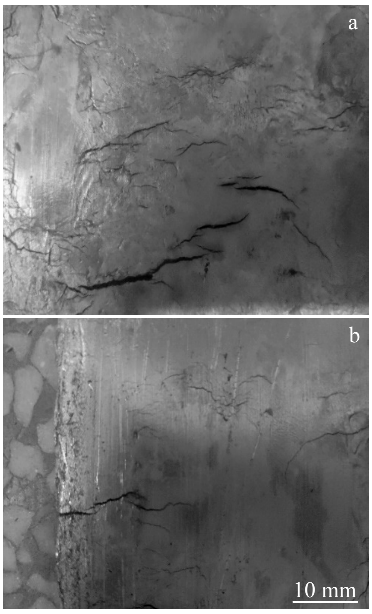

Fig.10 Macro morphologies of cracks at the edge (a) and core (b) in 7050 aluminum alloy cast-rolled plate

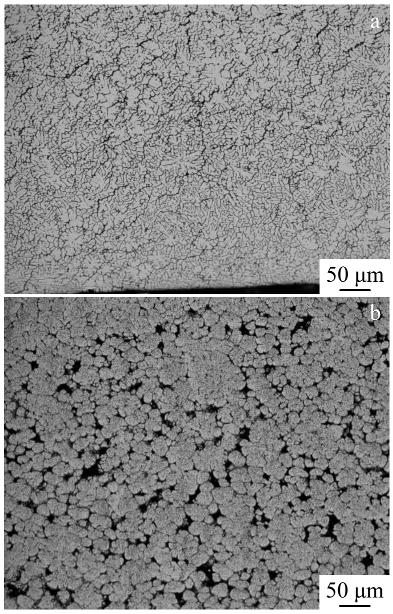

Fig.11 Microscopic grain morphologies of the surface layer edge (a) and the core (b) of the longitudinal section of the cast-rolled plate

interface of the matrix is weak, so it is easy to create pores at the junction of the phase and the matrix and form local stress concentration to form microcracks[28,29].

Fig.11 shows that the solidification process advances toward the center, the melt cooling rate decreases and the solidification rate decreases. Furthermore, most alloying elements are pushed to the solid-liquid phase interface and precipitated as a second phase. The grains then exist in the form of equiaxed crystals. In the cast-rolled sheet, an uneven grain structure will be observed. When cooling at the interface of adjacent grains, the liquid metal is not crystalline and the flow is restricted. The crystal grains may not be filled with the liquid metal and minute cracks may be generated by the tensile stress. However, when the microcracks reach a certain amount and under the action of the rolling force, cracking occurs and macroscopic cracks are generated.

2.6 Inhibition of Ti on the crack formation of TRC-7050

Refinement of grain: there are (100) Al_3Ti//(100) Al and other ten lattice planes with a mismatch of <5% between the Al_3Ti particles and the Al matrix[30]. Mohanty[31] reported that the Al_3Ti particles stay in the center of the Al grain. The results in Section 2.2 shows that the morphology of Al_3Ti phase in the cast-rolled plate with different Ti contents is very different. With the increase of Ti contents in the cast-rolled plate, the refinement effect of Al_3Ti particles continuously increases. The grain refining effect is the best when the Ti content is 0.2 wt% and the Al_3Ti has a fine block shape. The grain refinement can improve the overall performance of the cast-rolled structure and the fluidity of the alloy and eliminate local stress concentration in the alloy, thereby reducing the tendency of cracks during the cast-rolled process. However, excessive Ti causes the Al_3Ti phase to agglomerate and to form coarse and hard impurities as well as hard and brittle phases. Nevertheless, the number of effective heteronuclear nuclei is considerably reduced, resulting in weakening of grain refinement. In addition, the hardness of the coarse Al_3Ti phase is much higher than that of the matrix. During the cast-rolling process, these hard and brittle phases are easily crushed and the fracture of the hard and brittle phase of the aluminum alloy surface spreads to the surface, resulting in local stress concentration and formation of crack sources.

Reduction of the non-compensable interval: the crack source is usually generated in the non-compensable interval of the melt. The shrinkage can reduce the solidification defects such as shrinkage porosity during the solidification process of the alloy[32,33] and improve the alloy performance, reducing the non-retractable interval, so it is important to reduce the generation of cracks. The feeding flow of the alloy liquid is primarily carried out by a curved capillary channel formed by the interdigitation of the secondary dendritic arm solid phase skeleton[34,35] and the adjacent secondary dendritic arm solid phase skeleton. The addition of an appropriate amount of Ti element in the TRC-7050 can generate many dispersed heterogeneous nucleation cores, refine the crystal grains and transform the columnar crystal grains into fine uniform equiaxed grains, thereby suppressing the dendrite growth. The crystal grains in the structure of the cast-rolled sheet grow in a manner of equiaxed fine-grains. This helps to avoid a large amount of dendrites because the excessive cooling rate during the cast-rolling process can cause dendrite overlap. Therefore, it is difficult for intercrystalline melt to be closed and thus difficult to feed Ti, making the feeding channel of the 7050 alloy smooth during the cast-rolling process with a good solidification feeding effect. The cast-rolled alloy structure becomes denser, thereby suppressing the generation of grain boundary cracks.

Inhibition of component segregation: if we add an appropriate amount of Ti in the the TRC-7050, it can reduce the solid-liquidus temperature range, thereby reducing the supercooling of components because of solute enrichment, improving the distribution of solute elements and suppressing the occurrence of component segregation. Ti can not only refine the grain and non-equilibrium eutectic phase but also reduce the number of intercrystalline low-melting eutectic compounds, reducing the tendency of the cast-rolled alloy to generate stress concentration, and enhancing the resistance of the alloy to thermal cracking. Furthermore, Fe and Si have a significant effect on the hot brittleness of the aluminum alloy. The 7050 aluminum alloy is located in the rising part of the "silicon content-heat brittleness" curve, and Ti can react with some Fe and Si to form a new phase. The amount of free Si and the amount of eutectic in the alloy are reduced. The range of the brittle region is reduced, thereby improving the ability of the alloy to resist hot cracking.

3 Conclusions

1) The addition of trace amounts of Ti in the TRC-7050 can significantly refine the grain structure of the twin-roll cast-rolled plate, improve the overall properties of the cast-rolled structure and the fluidity of the alloy, and eliminate local stress concentration in the cast-rolled alloy, thereby decreasing the tendency of cracks. The optimal content of Ti is 0.2 wt%.

2) With addition of an appropriate amount of Ti into the 7050 cast-rolled plate, grain primarily grows in an equiaxed fine-grain manner, which ensures that the feeding channel of 7050 alloy during the twin-roll casting process is smooth, and the solidification feeding effect of the cast-rolled plate is good. The structure of the twin-roll cast-rolled alloy becomes denser and the generation of grain boundary cracks is effectively suppressed.

3) The addition of Ti can decrease the solid-liquid phase interval of the TRC-7050, reduce the temperature gradient of the nucleation solidification front, suppress the segregation of components because of element segregation, reduce the number of low-melting compounds at the grain boundary, reduce the coarse second phase, and enhance the heat crack resistance of the twin-roll cast-rolled aluminum alloy.

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钛对 7050 铸轧板材显微组织和裂纹调控的影响

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摘 要：采用场发射扫描电子显微镜，差示扫描量热仪，X 射线衍射仪等设备研究了微量 Ti 元素对 7050 铝合金铸轧薄板裂纹形成的影响规律和调控机理。结果表明：微量的 Ti 可以显著细化铸轧板的晶粒组织，改变晶粒生长方式，改善合金的流动性，使铸轧组织更加致密，消除合金内局部应力集中，抑制铸轧裂纹出现。而且，适量 Ti 元素还可以缩短铸轧 7050 铝合金的固液相线区间，减小晶核凝固前沿温度梯度，有效抑制成分偏析，从而降低晶界低熔点化合物数量，减少粗大第二相的产生，从而大幅增强铸轧铝合金的抗热裂能力。当 7050 铸轧板中 Ti 含量达到 0.2%（质量分数），Ti 对铸轧板裂纹的抑制作用最佳，而过量的 Ti 元素会聚集形成大块的含 Ti 脆性相，反而破坏组织的致密性，促进裂纹的萌生。

关键词：铝合金；铸轧；显微组织；裂纹

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