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ARTICLE

Effects of Zn Content on Microstructure and Cracks During Twin-Roll Casting of Al-Zn-Mg-Cu Cast-Rolled Strips

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Abstract: The microstructure and macroscopic cracks of five twin-roll casted Al-Zn-Mg-Cu alloys strips with various Zn contents (3.5wt%, 5wt%, 6.5wt%, 8wt%, and 10wt%) were investigated. The results show that the macroscopic cracks of strips decrease in numbers as the Zn content decreases from 10wt% to 5wt%, while this decrease is inhibited as the Zn content continuously decreases from 5wt% to 3.5wt%. The microstructure shows a transition from columnar crystals to equiaxed crystals along the surface to the center of the cast strip. The center segregation band of the cast strips becomes wider and the non-equilibrium coarse eutectic phases increase in amount as the Zn content increases in these Al-Zn-Mg-Cu strips. Unsolidified liquid phases and holes appear in the microstructure of strips with 10wt% Zn.

Key words: aluminum alloys; twin-roll casting; Al-Zn-Mg-Cu strips; crack

Al-Zn-Mg-Cu high-strength alloys have been extensively used as indispensable structural materials in the aeronautics industries, due to overall properties, such as high strength, low density and high resistance to fatigue[1-5]. Al-Zn-Mg-Cu alloy sheets through twin-roll casting process present advantages, such as short process, high efficiency and low cost[6-9]. Due to the wide crystallization range of Al-Zn-Mg-Cu alloy, the cracks of cast-rolled strips are difficult to control during actual production[10-15]. Birol et al[13] used differential scanning calorimetry to analyze the solidification behavior of 1050, 3003, 5754 and 6016 Al alloys during twin-roll casting. It was found that the 3003 and 5754 alloys are more susceptible to macrosegregation. Das et al[16] discovered that the surface segregation mostly occurs in aluminum alloys with wide crystallization intervals. Through the combination of simulation results obtained by the thermomechanical model of Al strip for twin-roll casting with the study of scanning electron microscopy (SEM) or microprobing, it was proposed that alloying elements in interdendritic liquids should be gradually enriched during solidification (micro-segregation). Under certain conditions, a low-pressure zone can form in the surface area, while the enriched liquid can flow through the condensed solid network to the surface, causing segregation along with solidification[17]. Gras et al[18] observed that in the center of aluminum alloy strip, the increase of rolling pressure leads to the increase of heat absorption rate, while the trapped solute-rich liquid rapidly solidifies to form complex eutectic structures. In certain studies, it was demonstrated that the alloy composition is an important factor affecting cracks in cast-rolled sheets. Zn is the most important alloy element in 7000 series aluminum alloys[19,20]. The content of Zn directly affects the final microstructure and mechanical properties of the alloys[21-23]. Seldom relevant researches about the effect of zinc on the cracks of cast-rolled Al-Zn-Mg-Cu alloys exist. In

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this study, five types of Al-Zn-Mg-Cu strips through twin-roll casting were prepared.

1 Experiment

Al-Zn-Mg-Cu strips with 3.5wt%, 5wt%, 6.5wt%, 8wt%, and 10wt% Zn were prepared with pure Al, pure Mg, pure Zn, Al-Cu, and Al-Zr master alloys through twin-roll casting, namely Zn3.5, Zn5, Zn6.5, Zn8, and Zn10, respectively. A NF8-300 vertical twin-roller caster was used. The composition of the experimental alloys is presented in Table 1. The casting temperature was 690 °C, the roll speed was 14 m/min and the roll gap was 2 mm. The length is 4 m, the width is 0.3 m and the thickness is 0.2 mm for each strip. The micrographs of the second-phase and fracture surface were examined with an EVO MA 10 scanning electron microscope (SEM). The chemical compositions of various particles were quantified through energy dispersive spectrometry (EDS). Differential scanning calorimetry (DSC) experiments were conducted with a TA Q2000 calorimeter. The DSC samples were machined from the alloy plates down to 3 mm in diameter and 1 mm in thickness with an approximate mass of 10 mg. The DSC parameters were heating rate of 10 K (10 °C)/min from 353 K to 973 K (25 °C to 700 °C).

2 Results

The macroscopic features of cast-rolled strips with Zn contents of 3.5wt%, 5wt%, 6.5wt%, 8wt%, and 10wt% are presented in Fig.1. Most cracks are transverse cracks as indicated in the macroscopic features of five strips. The shorter the crack length, the lower the depth. The number and length of cracks on the surface of strips with the same area are quantified, as presented in Fig.2. The number of cracks in cast-rolled strip is the lowest when the content of Zn is 3.5wt%. The number of cracks in cast-rolled strips is the highest when the content of Zn is 10wt%. Overall, the macroscopic cracks of strips increase as the Zn content increases from 5wt% to 10wt%. Most cracks are small cracks with length below 10 mm and depth below 0.1 mm. The crack length of cast-rolled strips is below 20 mm when the contents of Zn are 3.5wt%, 5wt%, and 6.5wt%. However, some cracks (area A in Fig.1d) are larger than 20 mm and longitudinal cracks (area B in Fig.1e) appear in the cast-rolled strip with the Zn contents of 8wt% and 10wt%.

The vertical section microstructures of cast-rolled strips with Zn contents of 3.5wt%, 5wt%, 6.5wt%, 8wt% and 10wt% are presented in Fig.3. The coarse eutectic structures are gathered together in the center of the cast-rolled strip to form a centerline segregation band, as presented through a red circle mark in Fig.3. No segregation bands are formed in

Table 1 Composition of experimental alloys (wt%)

Sample	Zn	Mg	Zn/Mg	Cu	Zr	Fe	Si	Al
Zn3.5	3.5	2	1.75	2	0.09	0.19	0.09	Bal.
Zn5	5	2	2.5	2	0.09	0.18	0.10	Bal.
Zn6.5	6.5	2	3.25	2	0.10	0.019	0.10	Bal.
Zn8	8	2	4	2	0.10	0.18	0.09	Bal.
Zn10	10	2	5	2	0.09	0.19	0.10	Bal.

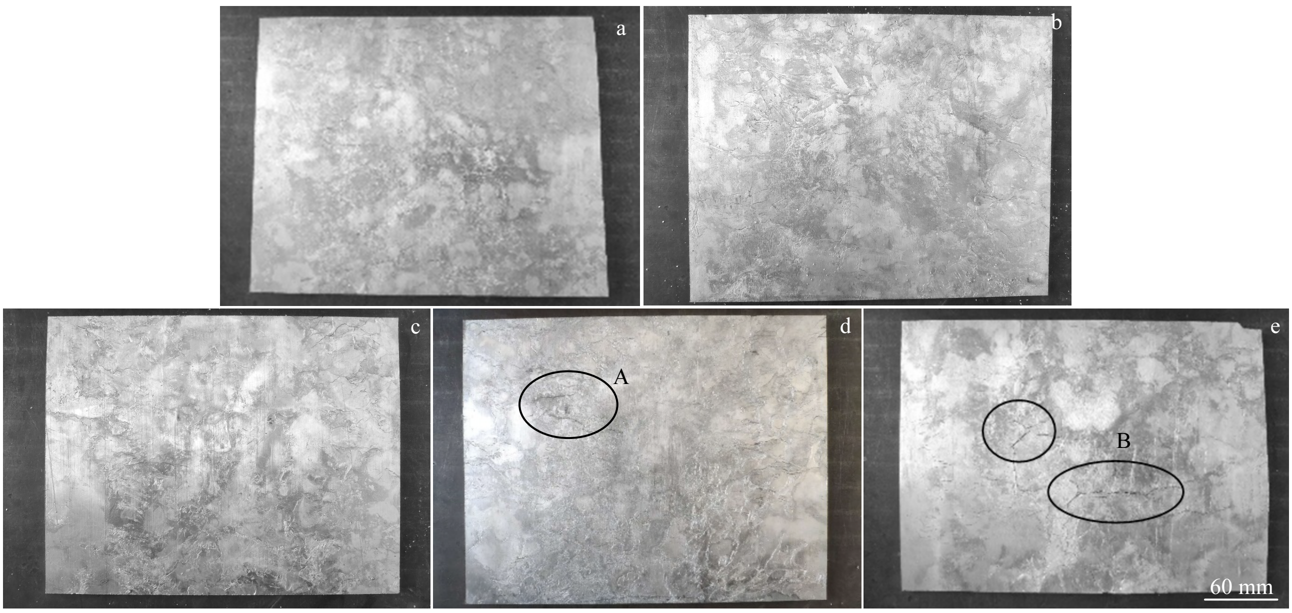

Fig.1 Macroscopic features of different cast-rolled strips: (a) Zn3.5, (b) Zn5, (c) Zn6.5, (d) Zn8, and (e) Zn10

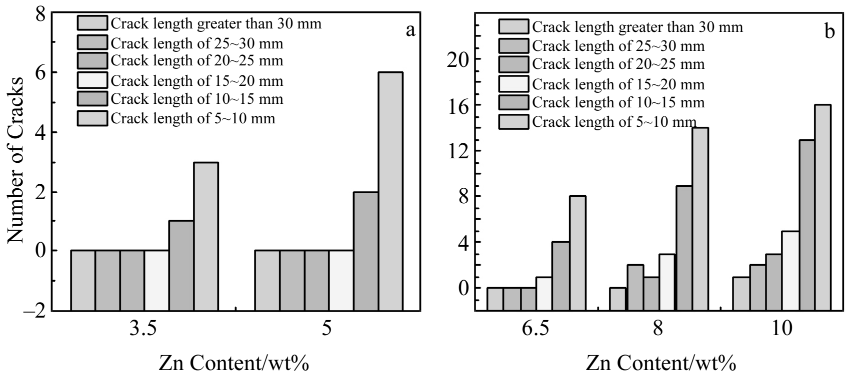

Fig.2 Statistical analysis on surface cracks of cast-rolled strips

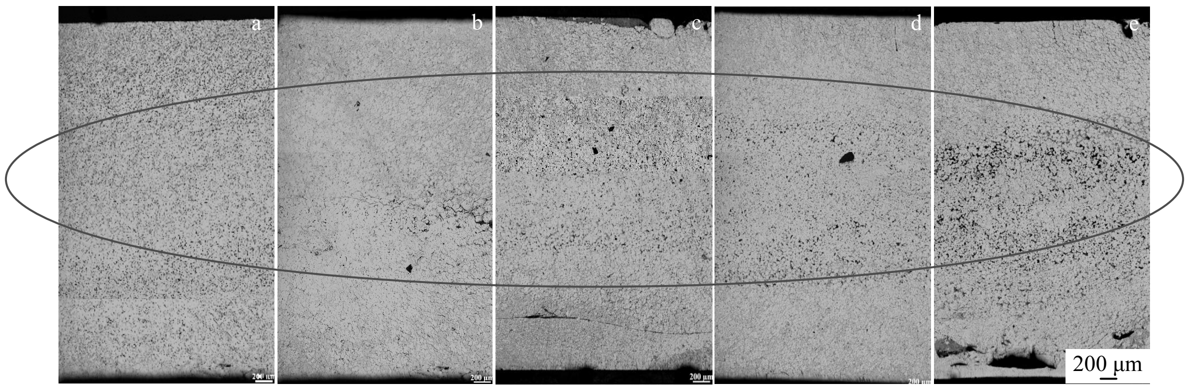

Fig.3 Vertical section microstructures of different cast-rolled strips: (a) Zn3.5, (b) Zn5, (c) Zn6.5, (d) Zn8, and (e) Zn10

Zn3.5, as presented in Fig.3a. The width of the segregation band increases significantly as the Zn content continuously increases from 3.5wt% to 5wt%.

The microstructure of cast-rolled strips with Zn content of 3.5wt%, 5wt%, 6.5wt%, 8wt%, and 10wt% is presented in Fig.4. The surface microstructures generate a high amount of nuclei to form chill crystals due to quenching. The microstructures near surface form developed dendrites, which grow perpendicularly to the rolling direction under the action of strong cooling. The decrease of heterogeneous nucleation points and the dendrite growth directions both lead to the formation of equiaxed crystals at the center of the strip, because the temperature gradient gradually decreases with the centripetal part extension. Therefore, the microstructure shows a transition of crystals from columnar to equiaxed along the surface to the center of the strip, as presented in Fig.4b. The direction of dendrite growth is inclined along a certain angle, as presented in Fig.4a. This occurs because the grain growth direction is opposite to the heat flow direction, while the heat flow direction is deflected due to the rotation of rolling. As the content of Zn increases, the dendrite gap becomes coarse, as presented in the areas A, B and C in Fig.4. This occurs because the solutes are mostly concentrated at the dendrite frontier. Solute-rich melt flows throughout the dendrite gap under the action of rolling pressure. The solute content increases as the Zn content increases. Consequently, the Zn10 phase is particularly apparent, as presented in Fig.4e. The coarse dendrite gap is a eutectic or pseudo-eutectic structure formed by non-equilibrium solidification of dendrites floating from the surface to the center. It has an adverse effect on the strength and plasticity of the alloy, which is probably a potential crack in the subsequent rolling treatment. Few coarse eutectic structures exist in the center of Zn3.5 and Zn5. However, large amounts of coarse eutectic structures exist in the center of Zn6.5, Zn8 and Zn10, as presented in the areas D, E and H in Fig.4. As the Zn content increases, the eutectic structures become larger. The reason for the center segregation band formation is that the central part of the strip is the final solidified region, while the solute is easy to redistribute. The composition of the solute is similar to the eutectic structure. Also, the coarse eutectic or pseudo-eutectic structure forms under the condition of rapid solidification. The properties of the low melting point eutectic phase are extremely poor, which severely affects the mechanical properties of the strip. It can be easily eliminated with heat treatments. Abnormal ultra-fine grains exist in the Zn8 and Zn10 phases, as presented in the areas G and F in Fig.4. These severely damage the structure uniformity. Moreover, holes exist in the Zn10 structure, as presented in Fig.4e.

The SEM images of cast-rolled strips with different Zn contents are presented in Fig.5. The structure of the cast-rolled strips is mainly composed of α-Al phase and the white network phase is continuously distributed along the grain boundary. EDS analysis of surface structures A and B (as

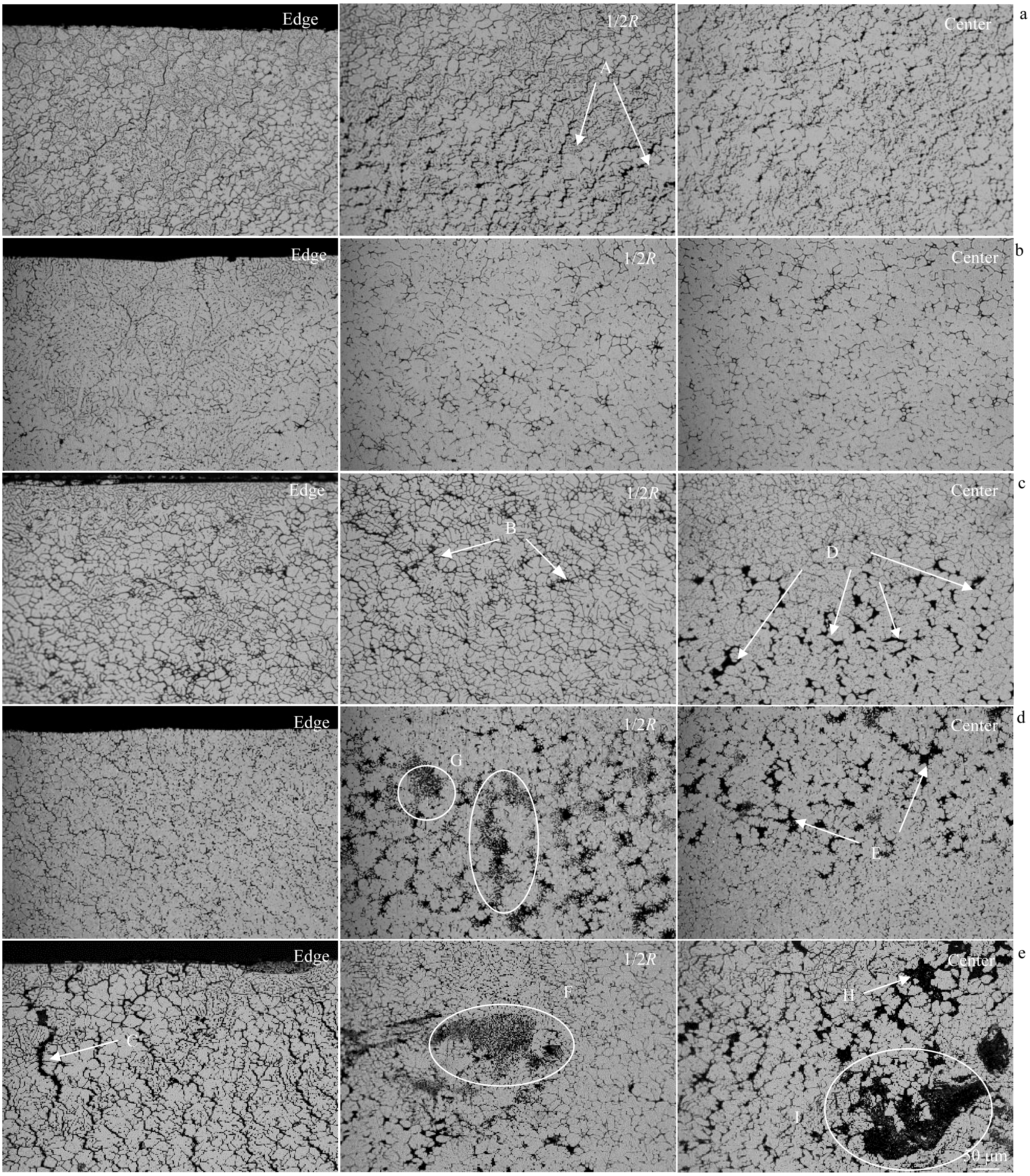

Fig.4 Microstructures of different cast-rolled strips: (a) Zn3.5, (b) Zn5, (c) Zn6.5, (d) Zn8, and (e) Zn10

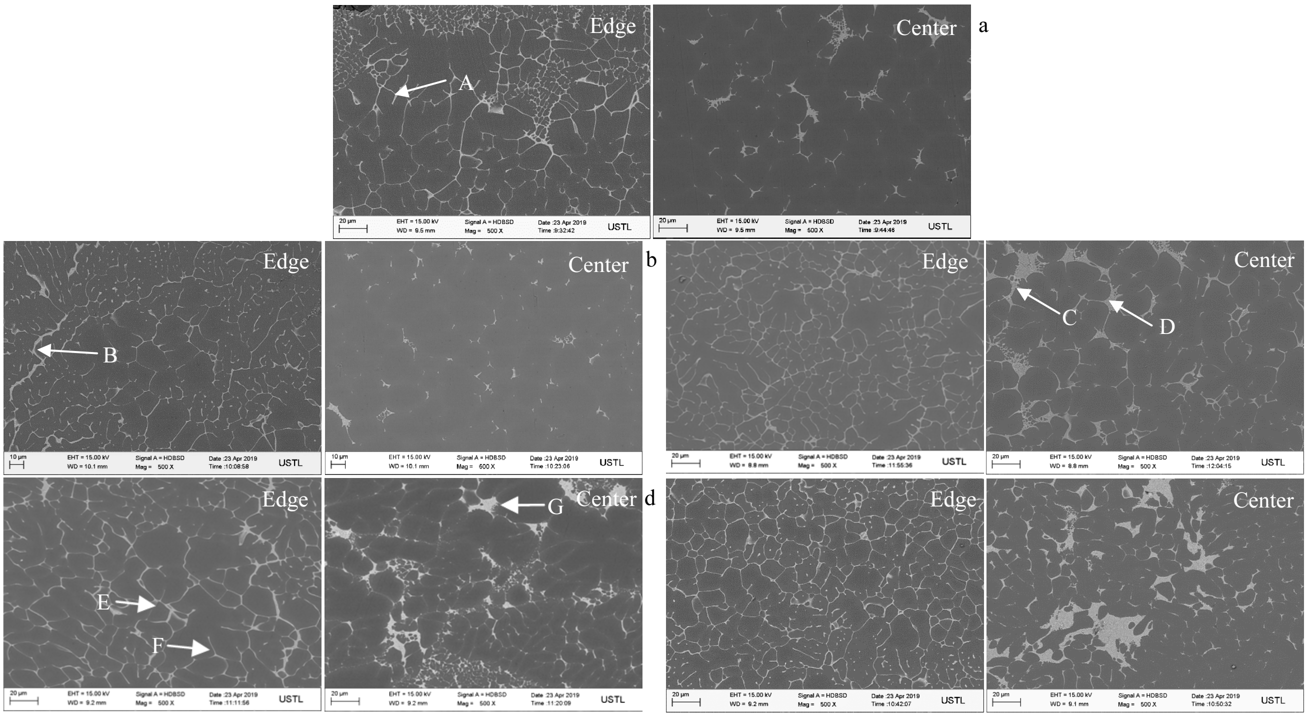

Fig.5 SEM images of different cast-rolled strips: (a) Zn3.5, (b) Zn5, (c) Zn6.5, (d) Zn8, and (e) Zn10

presented in Table 2) demonstrates that the white phase is distributed continuously along the grain boundary mainly due to the segregation of Zn, Mg and Cu at grain boundaries. Due to the direct contact between the surface microstructure and the roller, high cooling intensity leads to the formation of large amounts of dendrites, while solute-rich melts flow in the dendrite gap, resulting in the segregation of Zn, Mg and Cu at the grain boundaries. The centers are the final solidified parts, where the temperature gradient is low while the solutes are redistributed to form large eutectic phases. The white phase precipitated along the grain boundary of Zn3.5 and Zn5 surfaces is loose and intermittent, while the composition of the core structure is more uniform. Only a small amount of eutectic structure precipitates at the grain boundary intersection. The segregation of cast-rolled strips is lighter when the content of Zn is lower. The white phases precipitate along grain boundaries in the surface structure of Zn6.5, Zn8 and Zn10, becoming coarser as the Zn content increases. Also, the continuous distribution of the network is more compact. The spherical phase may be the Al_2CuMg phase and the acicular phase may be the $MgZn_2$ phase. The center precipitation phase is mainly composed of feather-like structure. Bright white precipitation phases and long strip phases are embedded in grey feather-like precipitation phases. The analysis result of

Table 2 Chemical composition of intermetallic phases in Fig.5 (at%)

Rolled strip	Mark point	Al	Zn	Mg	Cu	Identified phase
Zn3.5	A	60.61	9.50	22.21	7.68	AlZnMgCu
Zn5	B	62.57	9.48	18.90	9.05	AlZnMgCu
Zn6.5	C	44.52	13.19	31.44	10.84	AlZnMgCu
Zn6.5	D	60.72	10.49	20.43	8.37	AlZnMgCu
Zn8	E	67.53	1.69	16.55	14.22	Al_2CuMg
Zn8	F	81.49	10.65	6.67	1.18	$MgZn_2$
Zn8	G	42.64	12.88	30.28	14.20	AlZnMgCu

point D is similar to that of the points A and B, while the white phase of points C and G is the AlZnMgCu phase, as presented in Table 2.

The EDS analysis of feather-like structure is similar to that of the white phases, but the content of Al is higher. It should be a mixed zone of α-Al and AlZnMgCu phases. As the Zn content increases to 6.5wt%, 8wt% and 10wt%, the coarse non-equilibrium eutectic phase segregates at the grain boundary junction of the center structure. This type of coarse second phase often has very poor performance and easily becomes a potential crack initiation point for subsequent processing. The segregation becomes increasingly severe as the Zn content increases.

3 Discussion

Casting and rolling cracks occur because the surface of the slab in contact with the roller is subjected to shear stress from the roller during the solidification of the melt. Also, the melt in the molten state is subjected to stress beyond the maximum bearing capacity when it solidifies into the shell, resulting in plastic deformation, which leads to the generation of cracks. In addition, due to the uneven distribution of temperature at the crystallization front in the casting and rolling area, the temperature at the center of the casting and rolling plates differs from the surface temperature, while the solidification speed is not consistent, leading to crack formations in the melt prior to its solidification and feed initiation.

The microstructures of cracks are presented in Fig.6. It can be found that cracks always propagate along the main axis of dendrites. As the Zn content increases, the main dendrite crystal axis of the cast-rolled alloy structure gradually becomes thicker, which accelerates the crack propagation. Near the crack, ultra-fine grains exist, signifying that the liquid phase structure is not normally solidified. This occurs due to the failure of the melt to compensate in time. This phenomenon is more likely to occur in the cast-rolled structure with high Zn content. As the Zn content increases, the solid-liquid line range of the alloy becomes wider. The higher the crystallization interval, the more likely the alloy to undercool in composition, forming a large amount of dendrites, inhibiting the flow of liquid, as well as causing the liquid phase structure and the holes to be partially filled while forming cracks at the defect position under the shear force of rolling. Therefore, it can be concluded that as the Zn content increases, the solidification zone of the alloy becomes wider and the liquid flow becomes lower. Moreover, the liquid structure and hole defects with extremely poor mechanical properties are more likely to occur, which highly increases the crack formation probability.

Fig.7 presents the SEM images of the Zn8 and Zn10 hot rolling strips, and EDS spectrum of AlZnMgCu in Zn10. Coarse AlZnMgCu non-equilibrium phases are crushed to form cracks during subsequent rolling. Consequently, the coarse non-equilibrium structure is the potential source of cracking. The wide solidification temperature range, the high cooling speed on the strip surface and the low temperature gradient in the center of AlZnMgCu alloy eliminate the condition of equilibrium crystallization. This leads to the formation of a large amount of dendrites, liquid flow inhibition and reduction of diffusion ability of Zn, Mg and Cu within the solid solution. Due to selective crystallization during solidification, the liquid between the branches in the two-phase zone enriches a large amount of solutes. The alloy elements coalesce in the central segregation zone and the thick non-equilibrium eutectic structure is formed when the billet cools down subsequently. The coarse eutectic structure leads to difficult dislocation movement and the binding force with the matrix interface weakens. Cavitation and other defects between the compound and the matrix become the root cause of crack formation. The homogeneity of structure is severely affected and the cast-rolled aluminum alloy formability reduces. However, solute segregation becomes quite severe as the Zn content increases, as presented in Fig.2, which increases the crack formation probability.

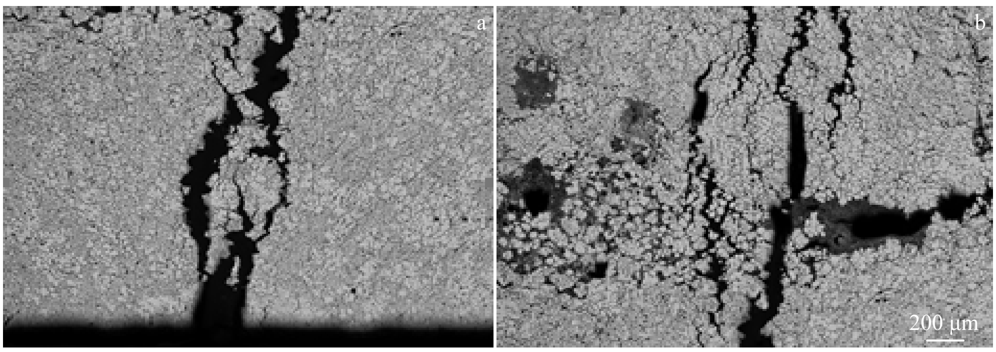

Fig.6 Microstructures of cracks in Zn8 (a) and Zn10 (b) cast-rolled strips

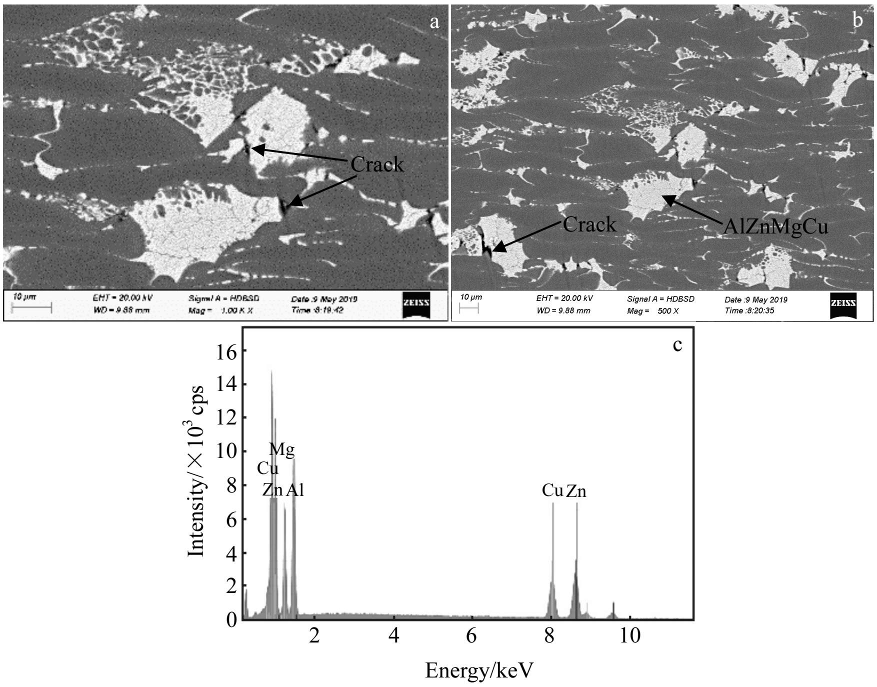

Fig.7 SEM images of hot rolling strips Zn8 (a) and Zn10 (b); EDS analysis of AlZnMgCu in Fig.7b (c)

4 Conclusions

1) The microstructure shows a transition from columnar crystals to equiaxed crystals along the surface to the center of the Al-Zn-Mg-Cu cast-rolled strips. As the content of Zn increases, the dendrite gaps become coarse. When the contents of Zn are 3.5wt% and 5wt%, small amounts of eutectic phases precipitate in the cast-rolled strip, while the coarse non-equilibrium eutectic phase precipitates in the cast-rolled strip when the content of Zn continuously increases from 6.5wt% to 10wt%. Also, the coarse phase size increases the eutectic zone width at the cast-rolled strip center.

2) As the Zn content increases, the number of cracks in the Al-Zn-Mg-Cu cast-rolled strip increases. The wider crystallization range makes the alloy easier to composition undercooling. The formation of a large amount of dendrites inhibits the liquid flow. Consequently, the concentrated solute liquid does not solidify, leading to formation of holes and cracks.

3) As the Zn content increases, solute segregation becomes quite severe, which increases the crack formation probability. The higher the Zn content, the more severe the non-equilibrium eutectic structure segregation. The coarse eutectic structure leads to difficult dislocation movement and reduces the binding force with the matrix interface. Moreover, the poor mechanical property is one of the root causes of crack formation.

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Zn 含量对 Al-Zn-Mg-Cu 铸轧板组织和裂纹的影响

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摘　要：研究了 3.5%，5%，6.5%，8%和 10%（质量分数）Zn 含量铸轧 Al-Zn-Mg-Cu 合金的宏观裂纹和微观组织。结果表明：Zn 含量由 10%减少至 5%时，铸轧条带的宏观裂纹数量明显降低；但当 Zn 含量由 5%减少至 3.5%时，裂纹数量减少十分有限。铸轧条带显微组织从表层到中心呈柱状晶向等轴晶的转变。随着 Zn 含量的增加，铸轧板中心低熔点共晶相偏聚带变宽，粗大非平衡共晶相数量增多，偏析加重。在高 Zn 含量（10%）的铸轧条带组织中有明显的孔洞存在。

关键词：铝合金；双辊铸轧；Al-Zn-Mg-Cu 条带；裂纹

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