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Liquid-solid interface control of BFe10-1-1 cupronickel alloy tubes during HCCM horizontal continuous casting and its effect on the microstructure and properties

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Abstract: Based on horizontal continuous casting with a heating-cooling combined mold (HCCM) technology, this article investigated the effects of processing parameters on the liquid-solid interface (LSI) position and the influence of LSI position on the surface quality, microstructure, texture, and mechanical properties of a BFe10-1-1 tube (ϕ50 mm × 5 mm). HCCM efficiently improves the temperature gradient in front of the LSI. Through controlling the LSI position, the radial columnar-grained microstructure that is commonly generated by cooling mold casting can be eliminated, and the axial columnar-grained microstructure can be obtained. Under the condition of 1250°C melting and holding temperature, 1200-1250°C mold heating temperature, 50-80 mm/min mean drawing speed, and 500-700 L/h cooling water flow rate, the LSI position is located at the middle of the transition zone or near the entrance of the cooling section, and the as-cast tube not only has a strong axial columnar-grained microstructure ({*hkl*}<$6\bar{2}1$>, {*hkl*}<$2\bar{2}1$>) due to strong axial heating conduction during solidification but also has smooth internal and external surfaces without cracks, scratches, and other macroscopic defects due to short solidified shell length and short contact length between the tube and the mold at high temperature. The elongation and tensile strength of the tube are 46.0%-47.2% and 210-221 MPa, respectively, which can be directly used for the subsequent cold-large-strain processing.

Keywords: copper-nickel alloys; tubes; continuous casting; interfaces; textures; mechanical properties

1. Introduction

BFe10-1-1 cupronickel alloy (BFe10 for short, shown in Table 1) is used to produce condenser tubes and heat exchanger pipes in thermal power, ships, desalination, and other fields due to its high strength, good thermal conductivity, and excellent corrosion resistance [1]. The traditional process to produce cupronickel alloy tubes is semi-continuous casting solid ingot → hot extrusion → cold rolling → drawing, which is hereinafter referred to as ‘extrusion-rolling’ method. However, the total process, including multiple passes of cold rolling/drawing, acid washing, and intermediate annealing, needs more than 20 passes, which results in a series of problems, such as long process flow, high-energy consumption, low tube yields, and high cost [2].

In recent years, horizontal continuous casting (cooling mold casting, CMC) for direct production of tubes has attracted a lot attention due to its high yield rate and low production costs. However, the CMC method has several problems. For example, an as-cast tube has poor quality of internal and external surfaces (tangerine peel, folds, cracks, etc). Thus, the external and internal surface treatment of the tube is required before the subsequent processing of the tube, which inevitably increases the processing procedure and decreases the product yield. In addition, the as-cast tube produced by the CMC method is composed of columnar grains along the radial direction and has low density, which reduces the axial extension deformation during its subsequent cold processing (rolling and drawing).

The authors [3-4] proposed to produce thin-wall and

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small-diameter copper and copper alloy tubes using the continuous unidirectional solidification (OCC) [5] technology, and the obtained tubes can be directly processed into small pipes, which established a compact process of highly efficient fabrication of precision tubes. OCC can produce the tube with a mirror-class surface and a continuous columnar-grained microstructure along the axial direction, which has a 49% elongation at room temperature, and is particularly beneficial to the subsequent cold processing [3]. During OCC, the liquid-solid interface (LSI) should be located at the outlet of the mold, and thus, the mold needs to be heated to a temperature higher than the melting point of the alloy. Such a behavior tends to induce breakout accidents and large fluctuation of processing parameters when the casting speed is fast [3]. Furthermore, the OCC method is suitable only for producing tubes with small diameter (< 40 mm) and thin wall (< 3 mm) at a relatively slow casting speed (< 40 mm/min), due to the restriction of high-temperature gradient in the drawing direction.

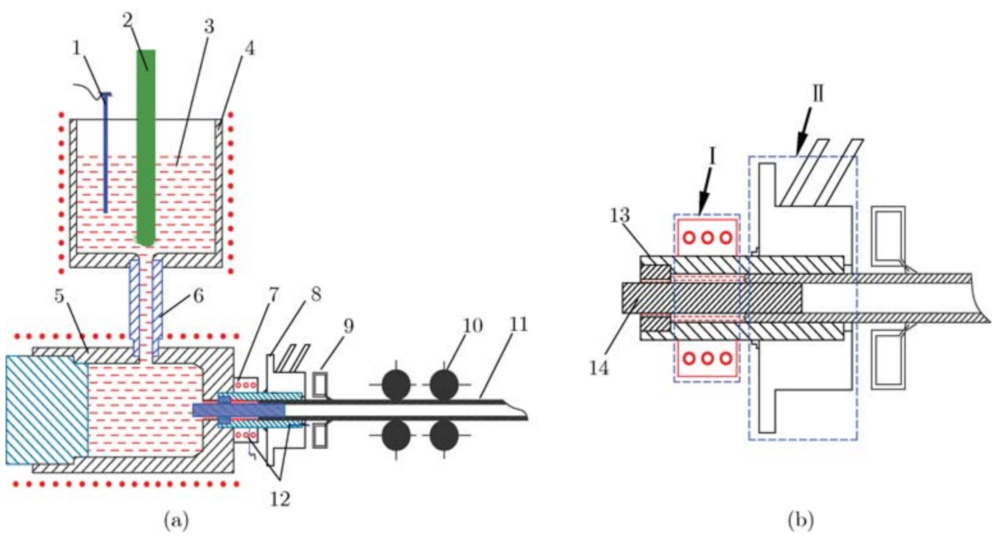
In order to overcome the problems mentioned above for producing BFe10 alloy tubes, the authors [6] have developed a novel horizontal continuous casting method by designing a new type of casting mold that combined the heating function and cooling function together and it was named by the heating-cooling combined mold (HCCM). The HCCM technology not only solves the breakout problem of the OCC method but also successfully increases the diameter and wall thickness and increases the casting speed, which approaches to the level of the CMC method. By controlling the heating-sectional temperature and cooling-sectional cooling intensity of the combined mold, the high-temperature gradient can be established in front of LSI, the radial columnar-grained microstructure produced by the CMC method can be eliminated, and a strong axial-columnar-grained microstructure with high density and high surface quality (without surface defects, such as tangerine peels, folds and cracks) can be achieved [7-8]. In HCCM horizontal continuous casting, the LSI position has a strong effect on the microstructure and mechanical properties of the tube and on the contact condition between the tube and the mold, which affects the surface quality of the tube. Therefore, the key of HCCM horizontal continuous casting is to accurately control the LSI position.

In the present work, the effects of processing parameters (mold heating temperature, mean drawing speed, and cooling water flow rate) on the LSI position and the effect of the LSI position on the microstructure, mechanical properties, and surface quality of the BFe10 alloy tubes produced by HCCM horizontal continuous casting are studied.

2. Experimental

2.1. Process principle and experimental set-up

Fig. 1 shows the schematic of HCCM horizontal continuous casting that is composed of a melting system (2 and 4), a temperature holding system (5 and 6), and a continuous casting system (7, 8, 9, 13, and 14), and the function of each part is referred to Ref. [7]. The LSI position can be controlled by adjusting the melt temperature, mold heating temperature, mean drawing speed, and cool-



1—temperature measuring device; 2—stopper; 3—alloy melt; 4—melting crucible; 5—holding crucible; 6—diversion pipe; 7—mold heating device; 8—water-cooled copper sleeve; 9—secondary cooling water; 10—traction device; 11—tube; 12—temperature measuring device; 13—mold; 14—core rod; I—section of heating mold; and II—section of cooling mold.

Fig. 1. Schematic view of heating-cooling combined mold (HCCM) casting [7]: (a) process principle and (b) structure of HCCM.

ing water flow rate.

The novel feature of HCCM horizontal continuous casting is that the mold consists of a heating section and a cooling section. The mold heating section is heated by induction coils, and the heating temperature is higher than the melting point of the alloy. A forced cooling is performed at the cooling section with a water-cooling copper sleeve. Through this technology, a high enough axial temperature gradient in front of LSI can be obtained inside the transition zone between the heating section and the cooling section, as indicated by dashed line frames in Fig. 1(b). HCCM can increase the density of tube and promote the grain growth along the axis, which favors to obtain the crystal structure along the axial direction and suppress columnar grains along the radial direction. Meanwhile, the LSI position could be adjusted within a wide region between the heating section and the cooling section, which will avoid breakout [3] and produce larger diameter and thick wall tubes at a fast drawing speed.

The main factors of HCCM horizontal continuous casting are melting and holding temperature (T_1), mold heating temperature (T_M), mean drawing speed (V), and cooling water flow rate (Q). In order to reduce the burning loss during alloy remelting, T_1 is only required to ensure alloy melt to flow into the mold. Therefore, the LSI position can be controlled by adjusting T_M, V, and Q, setting T_1 as a fixed parameter. BFe10 alloy materials were used in the current study, and the standard and analyzed compositions are given in Table 1. The processing parameters of BFe10 tubes produced by HCCM are listed in Table 2.

Table 1. Chemical composition of BFe10-1-1 (reference to GB/T 5234–2001) wt%

Composition type	Ni	Fe	Mn	Cu
Standard composition	9.0-11.0	1.0-1.5	0.5-1.0	Balance
Analyzed composition	10.7	1.1	0.9	Balance

Table 2. Processing parameters of BFe10 tubes produced by HCCM casting

Serial No.	T_M / °C	V / (mm·min^{-1})	Q / (L·h^{-1})
1	1150	50	700
2	1200	50	700
3	1250	50	700
4	1300	50	700
5	1200	20	700
6	1200	50	700
7	1200	80	700
8	1200	110	700
9	1200	50	300
10	1200	50	500
11	1200	50	700
12	1200	50	900

Note: the casting tube size is ϕ50 mm× 5 mm; the melting and holding temperature (T_1) is 1523 K (1250°C); Nos. 2, 6, and 11 in the table are with the same processing parameters.

2.2. Analysis and test methods

Surface morphology of the as-cast tube was pictured using a digital camera. Specimens were cut from the transversal section (TS) and the longitudinal section (LS) of BFe10 tubes by wire cutting, as shown in Fig. 2. The TS and LS specimens were polished and etched by a solution of HNO_3 40 mL + CH_3COOH 40 mL + H_2O 20 mL for optical observation. Microstructure observation was performed using an LV150 optical microscope (OM). The texture of the as-cast tubes was measured using a Siemens D5000 X-ray diffractometer, and the results were shown in the orientation distribution function (ODF) (φ_2 = constant). The tensile test was performed on an MTS testing machine based on the GB/T228–2002 standard. The external surface roughness of the as-cast tubes was tested with a TIME TR200 surface roughometer with a 0.01 μm accuracy.

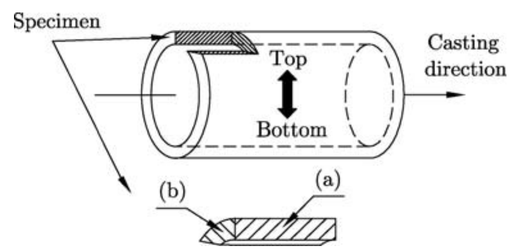


Fig. 2. Schematic diagram of sampling position and method to prepare specimens: (a) longitudinal section of the tube (LS) and (b) transversal section of the tube (TS).

3. Results and discussion

3.1. Effects of processing parameters on the LSI position

During the HCCM horizontal continuous casting of BFe10 tubes, the LSI position was dominated by processing parameters, such as mold heating temperature, mean drawing speed, and cooling water flow rate. The parameters used in the present work are listed in Table 2. After each experiment, the graphite mold, shown in Fig. 3(a), was taken out and cut along the axis, and then, the inner surface of the mold was observed [8]. An example of the inner radius surface of the mold is shown in Fig. 3(b).

Due to the effect of the gravity, there is an air gap between the solidified shell and the top of the graphite mold, and the friction between the solidified shell and the bottom of the graphite mold is strong, which induced reoxidation and wear during the casting. From the initial position of the scratch and the position of the metal film (shown in Fig. 3(b)), the LSI position can be determined by measuring L_1 and L_2 beginning from the mold end, respectively, which is the white dotted line shown in Fig. 3. The left side of the dotted line is the unset zone (liquid state + mushy zone), while the right side is the solidified zone (solid state). The actually measured LSI positions under different processing parameters (Table 2) are shown in Fig. 4.

It should be mentioned that the method described above was used to determine the LSI position by measuring the solidification end of the external surface of the tube, while the solidification end in the radial direction of the tube wall, i.e., the shape of LSI, varied with processing parameters, as shown in Fig. 5.

In Fig. 4(a), when the mold heating temperature increases from 1150 to 1300°C, the LSI moves toward mold outlet inside the transition zone, L_{Tran}(~25 mm) between the heating section and the cooling section, which hardly enters the cooling section. In addition, the angle between the LSI and the axial direction increases, implying a small difference between the solidification interface positions of the top and bottom of the tube. When the mean drawing

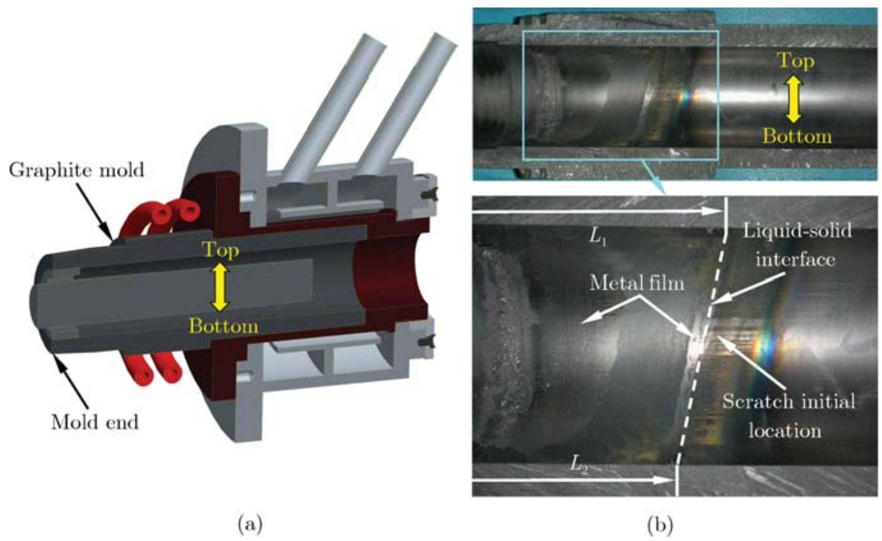


Fig. 3. Schematic diagram of mold location (a) and internal surface morphology of the mold after casting (b) [8].

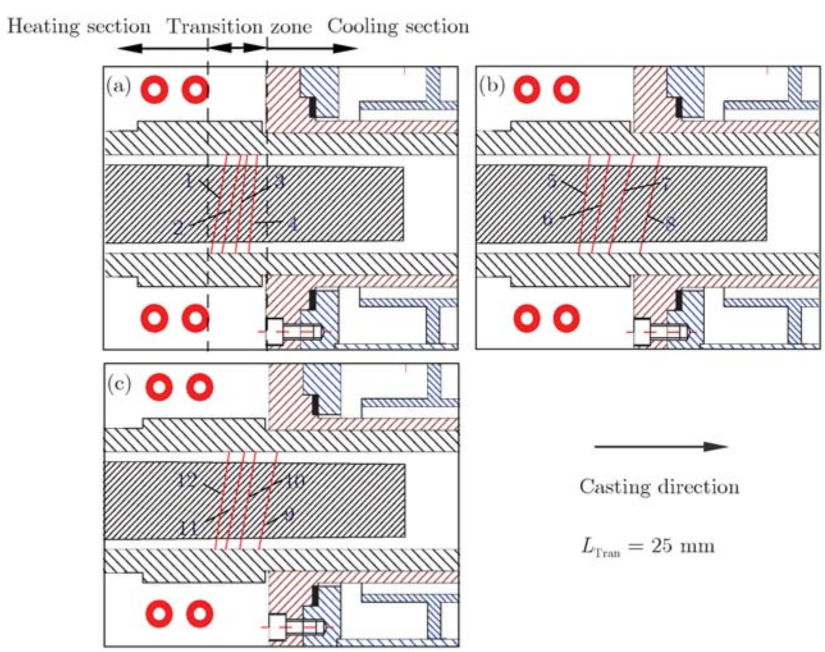


Fig. 4. Schematic diagram of the LSI position of cast BFe10 tubes under different processing parameters: (a) mold heating temperature; (b) drawing speed; (c) cooling water flow. 1—1150°C; 2—1200°C; 3—1250°C; 4—1300°C; 5—20 mm/min; 6—50 mm/min; 7—80 mm/min; 8—110 mm/min; 9—300 L/h; 10—500 L/h; 11—700 L/h; 12—900 L/h (reference to Table 2).

speed increases from 20 mm/min to 110 mm/min, the LSI also moves toward mold outlet inside the transition zone. When the speed is less than 80 mm/min, the LSI is always out of the cooling section. When the speed increases to 110 mm/min, the LSI moves into the cooling section and the angle decreases, as shown in Fig. 4(b). The effect of cooling water flow rate is contrary to the results above. With the cooling water flow rate increasing from 300 L/h to 900 L/h, the LSI position moves toward the inside of the mold. The LSI position is located at the entrance of the cooling section at 300 L/h water flow rate. Increasing the cooling intensity causes the LSI to move into the transition zone, as shown in Fig. 4(c).

The LSI position affected by processing parameters inevitably has a great effect on the microstructure, texture, and mechanical properties of the tube, which will be discussed in the following section.

3.2. Effect of the LSI position on the microstructure, texture and mechanical properties of BFe10 tubes

During HCCM horizontal continuous casting, the LSI position is mainly determined by heat conduction during the solidification of the tube. The LSI shape changed with its position. It can be speculated that the LSI position also has a significant effect on the microstructure of the tube. According to the LSI positions observed in the current experiments, five different zones from the heating section to cooling section is classified as follows: (1) near the heating section exit, (2) middle of the transition zone, (3) near the cooling section entrance, (4) entrance of the cooling section, and (5) inside the cooling section, as shown in Fig. 5 (left). Fig. 5 (right) shows the LSI shape along the radial direction of the tube, which were obtained by the numerical simulation of the temperature field during HCCM horizontal continuous casting of BF10 tubes [8]. The corresponding microstructures of the tubes are shown in Fig. 6, and their texture and orientation density are listed in Table 3.

In Figs. 6(a) and 6(b), when the LSI of the as-cast tube is located near the heating section exit ((1) in Fig. 5), the tube exhibits tightly arranged and axial-growing columnar dendrites with coarsening primary dendrite trunks, which have a small angle with the axial direction. More uniform "+" shape ends of columnar dendrites are observed from a transversal section. Fig. 6(c) and Table 3 indicate that this tube has a strong casting texture with the main orientation of $\{hkl\}<5\bar{1}0>$, and its orientation density is 40, which may be induced by the straight LSI (Fig. 5), the heat conduction during solidification mainly along the axial direction, and the high-temperature gradient built in front of the LSI. When the LSI is located at the middle of the transition zone ((2) in Fig. 5), the tube still has the axial-columnar-grained microstructure with coarsening primary dendrite trunks, but the angle between the primary dendrite and the axial direction increases and the secondary dendrite slightly grows. The transversal section microstructure in Fig. 6(e) is also not as uniform as that in Fig. 6(b). The tube has strong casting texture with a main $\{hkl\}<6\bar{2}1>$ orientation and a 31 orientation density.

When the LSI moves toward the cooling section entrance, the texture density of the tube decreases. When the LSI is located near the cooling section entrance ((3) in Fig. 5), the angle between primary dendrite trunk and axial direction greatly increases, the main texture of the tube is $\{hkl\}<2\bar{2}1>$, and its density decreases to 28, as shown in Figs. 6(g)-6(i). When the LSI is located at the cooling section entrance ((4) in Fig. 5), some abnormal grains generate in the tube, especially some grains tend to grow along the radial direction. The main texture of the tube is $\{hkl\}<2\bar{3}3>$, and its density decreases to 18, as shown in Figs. 6(j)-6(l). When the LSI moves to the inside the coo-

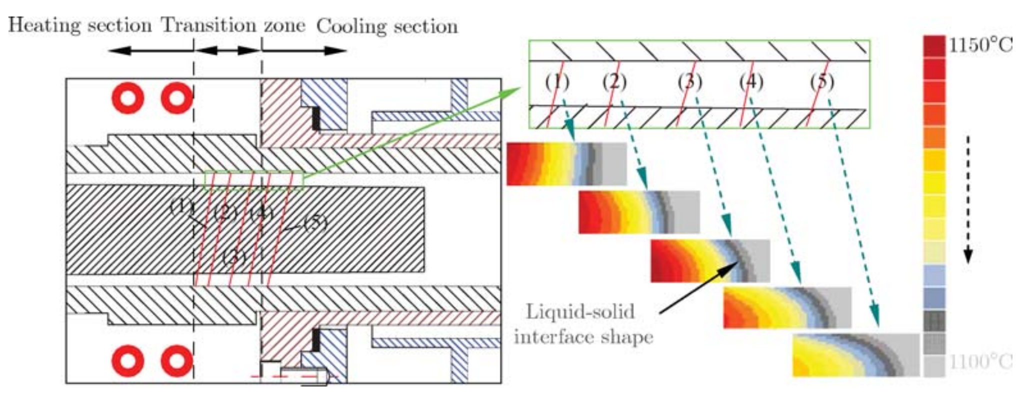


Fig. 5. Position and shape (simulation) of LSI for BFe10 cast tubes [8]: (1)—ear the heating section exit (T_M = 1150°C, V = 50 mm/min, Q = 700 L/h); (2)—iddle of the transition zone (T_M = 1200°C, V = 50 mm/min, Q = 700 L/h); (3)—ear the cooling section entrance (T_M = 1200°C, V = 80 mm/min, Q = 700 L/h); (4)—ntrance of the cooling section (T_M = 1200°C, V = 50 mm/min, Q = 300 L/h); (5)—nside the cooling section (T_M = 1200°C, V = 110 mm/min, Q = 700 L/h).

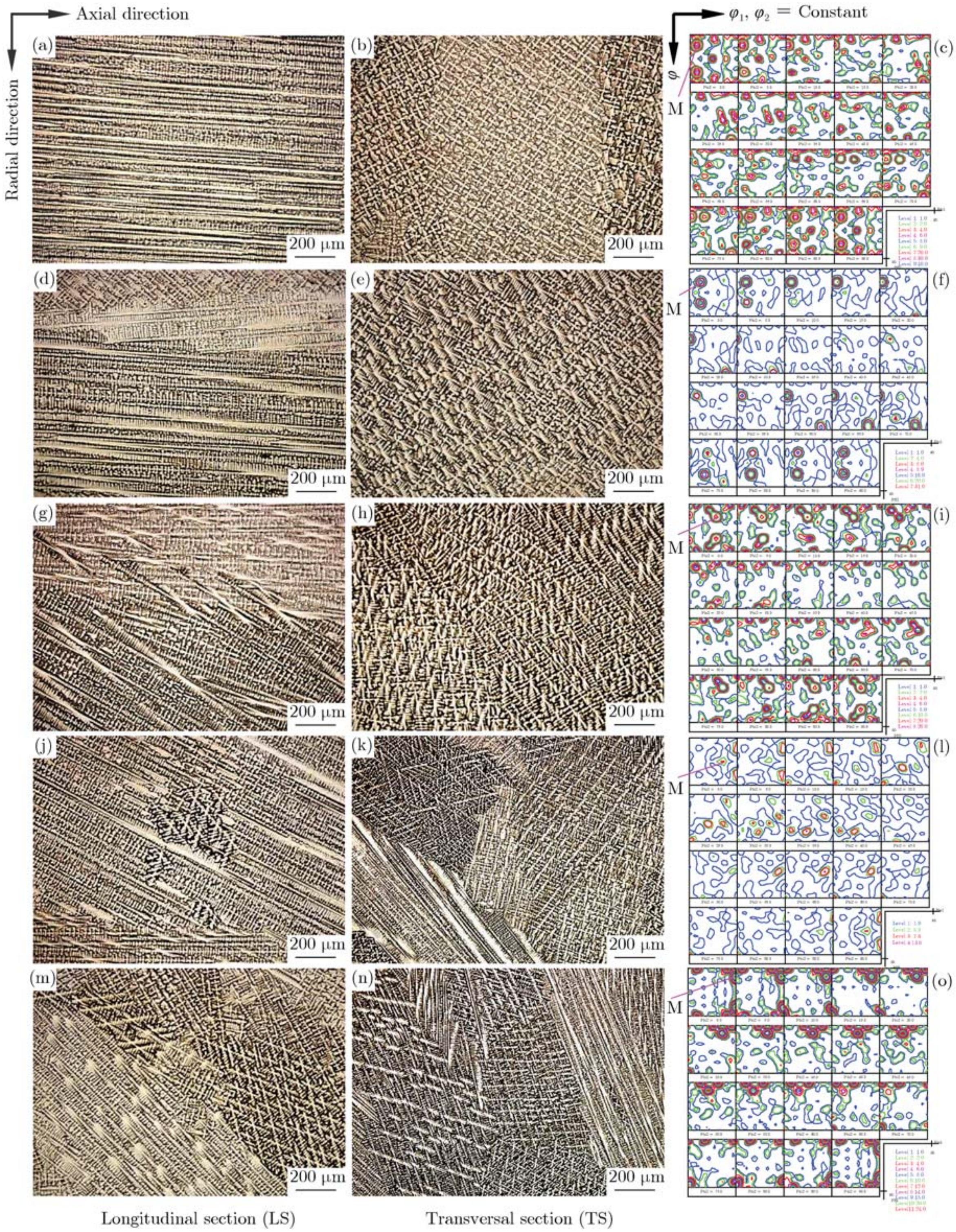


Fig. 6. Microstructures and ODFs of cast BFe10 tubes with different LSI positions in Fig. 5: (a)-(c) with position (1), (d)-(f) with position (2), (g)-(i) with position (3), (j)-(l) with position (4), and (m)-(o) with position (5). LS contains (a), (d), (g), (j), and (m); TS contains (b), (e), (h), (k), and (n). "M" in the ODF figure above represents the "main texture" as shown in Table 3.

Table 3. Main texture of cast BFe10 tubes with different LSI positions

LSI position	Main texture	Orientation density	Fabrication parameter
(1) Near the heating section exit	$\{hkl\}<5\bar{1}0>$, Fig. 6(c)	40	(1) in Fig. 5
(2) Middle of transition zone	$\{hkl\}<6\bar{2}1>$, Fig. 6(f)	31	(2) in Fig. 5
(3) Near cooling section entrance	$\{hkl\}<2\bar{2}1>$, Fig. 6(i)	28	(3) in Fig. 5
(4) Entrance of cooling section	$\{hkl\}<2\bar{3}3>$, Fig. 6(l)	18	(4) in Fig. 5
(5) Inside cooling section	$\{hkl\}<0\bar{3}1>$, Fig. 6(o)	24	(5) in Fig. 5

ling section ((5) in Fig. 5), the tube has columnar grains along the radial direction with the main texture of $\{hkl\}<0\bar{3}1>$, and its density increases to 24, as shown in Figs. 6(m)-6(o). With the LSI moving toward the cooling section, the radial heat conduction of tube gradually increases, which results in the increase of the bending degree of the LSI. When the LSI moves into the cooling section, the bending degree is the biggest and a deep liquid cave is generated, as shown in Fig. 5. The radial heat conduction becomes predominant during solidification, which induces an increase of the radial oriented microstructure and a decrease of the axial oriented microstructure, leading to an increase of the texture density of the radial oriented microstructure.

Mechanical property tests of the as-cast tubes with five kinds of different microstructures (Fig. 6) were performed, which corresponded to the different LSI positions (Fig. 5). The test results are shown in Fig. 7, and both their tensile strength and elongation are listed in Table 4.

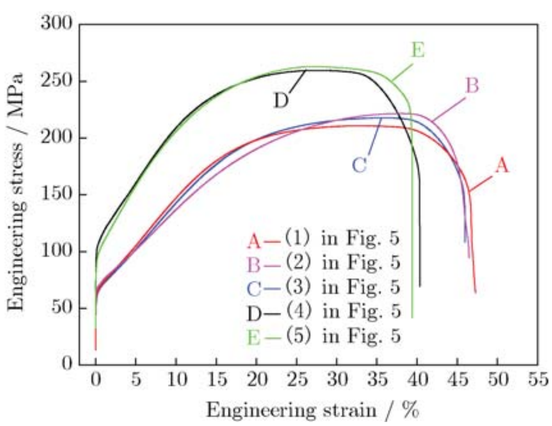


Fig. 7. Engineering stress-engineering strain curves of BFe10 cast tubes with different LSI positions.

The microstructure of the tubes with different LSI positions could be classified into two categories, i.e., the strong axial-columnar-grained microstructure and the radial-columnar-grained microstructure. When the LSI position is completely within the transition zone (interface position shown by (1), (2), and (3) in Fig. 5), the as-cast tube has axial columnar grains with an over 46.0% elongation and a 210-221 MPa tensile strength. When the LSI is at the cooling section entrance or inside the cooling section, the radial columnar grains increasingly forms, which significantly decreases the elongation of the tube and increases its tensile strength. With the LSI at the cooling section entrance ((4) in Fig. 5), the elongation of the tube decreases to 40.4%, and its tensile strength increases to 256 MPa. When the LSI is inside the cooling section ((5) in Fig. 5), the elongation of the tube is 39.3%, and its tensile strength is 263 MPa.

Table 4. Tensile strength and elongation of cast BFe10 tubes with different LSI positions

Specimen No.	LSI position	Tensile strength /MPa	Elongation / %
A	(1) in Fig. 5	210	47.2
B	(2) in Fig. 5	221	46.4
C	(3) in Fig. 5	218	46.0
D	(4) in Fig. 5	256	40.4
E	(5) in Fig. 5	263	39.3

Fig. 8 shows the tensile fracture morphologies of the tubes with the strong axial-columnar-grained microstructure (Figs. 8(a) and 8(c)) and the radial-columnar-grained microstructure (Figs. 8(b) and 8(d)). There are a great number of dimples on the tensile fracture, indicating that ductile fracture occurred on both tubes. However, the tube with the strong axial-columnar-grained microstructure exhibits fibrous tensile fracture, consisting of many deep dimples, as shown in Figs. 8(a) and 8(c), while the tube with the radial-columnar-grained microstructure shows the relatively flat tensile fracture with some steps and shallow dimples, as shown in Figs. 8(b) and 8(d).

It can be concluded that during HCCM horizontal continuous casting, when the LSI is within the transition zone between the heating section and the cooling section, the as-cast tube has a strong axial-columnar-grained microstructure with an excellent ductility ($\delta = 46.0\%$-47.2%). When the LSI is located at the cooling section entrance or inside the cooling section, the as-cast tube mainly exhibits a radial-columnar-grained microstructure.

The Schmid factors of different main textures according to microstructure with different LSI positions are shown in Table 5.

The calculated Schmid factors (shown in Table 5) indicate that in the current study the difference in activating difficulties of dislocation slip systems between the strong axial-columnar-grained microstructure and radial-columnar-grained microstructure is little, i.e., all the Sch-

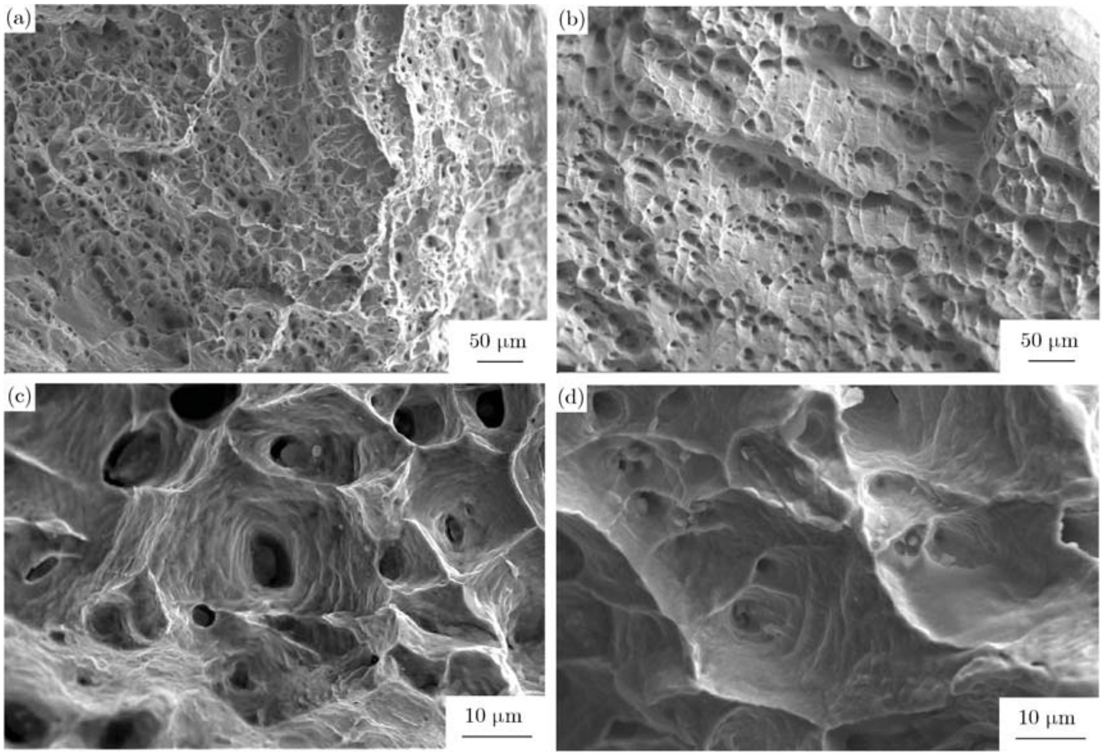


Fig. 8. Tensile facture morphologies of BFe10 cast tubes with two types of microstructures: (a) and (c) axial-columnar-grained microstructure; (b) and (d) radial-columnar-grained microstructure.

Table 5. Schmid factors for main textures of cast BFe10 tubes with different LSI positions

Slip plane	Slip direction	Slip system	$\{hkl\}<5\bar{1}0>$	$\{hkl\}<6\bar{2}1>$	$\{hkl\}<2\bar{2}1>$	$\{hkl\}<2\bar{3}3>$	$\{hkl\}<0\bar{3}1>$
	$\bar{1}10$	a1	0.38	0.4	0.18	0.19	0.25
111	$0\bar{1}1$	a2	0.06	0.15	0.13	0.22	0.33
	$\bar{1}01$	a3	0.31	0.25	0.05	0.04	0.08
	110	b1	0.38	0.36	0	0	**<u>0.49</u>**
$1\bar{1}1$	011	b2	0.38	0.09	0.23	0.15	0.32
	$\bar{1}01$	b3	**<u>0.48</u>**	0.45	0.23	0.15	0.16
	110	c1	0.38	0.28	0	0.04	0.25
$\bar{1}11$	101	c2	**<u>0.48</u>**	**<u>0.47</u>**	**<u>0.4</u>**	0.19	0.08
	$0\bar{1}1$	c3	0.38	0.21	**<u>0.4</u>**	0.22	0.33
	$\bar{1}10$	d1	0.38	0.24	0.18	**<u>0.37</u>**	**<u>0.49</u>**
$11\bar{1}$	011	d2	0.06	0.03	0.05	0	0.32
	101	d3	0.31	0.21	0.13	**<u>0.37</u>**	0.16

mid factors approach to the maximum value of 0.5 on the unidirectional load deformation [9-11]. This implies that the change of the texture is irresponsible for the difference in mechanical properties of the tubes with the strong axial-columnar-grained microstructure and radial-columnar-grained microstructure. During the axial tensile deformation, since the axial-columnar-grained microstructure has less transverse grain boundary than the radial-columnar-grained microstructure [12], the ductility of the axial-columnar-grained microstructure is superior to that of the radial-columnar-grained microstructure. Therefore, during the axial tensile deformation, the mean free path of dislocation slipping along the axis in grains is greater, and the dislocation density caused by dislocation accumulation is smaller. Thus, the work hardening rate of materials is slow during deformation, and the materials can exhibit a greater tensile deformation before being damaged [13-14].

3.3. Effect of the LSI position on the surface quality of BFe10 tubes

In HCCM horizontal continuous casting, the LSI position has significant impacts on the surface quality of the tube. Fig. 9 shows the schematic diagram for the LSI position and shape during HCCM horizontal continuous casting. The LSI shape is closely related to the LSI position, which ultimately has an effect on the solidified shell length (L_S) and the contact condition between the tube surface and the mold. When the LSI is close to the heating section exit (Fig. 9(a)), the heat conduction during solidification is mainly along the axial direction, and the LSI is straight, which induces a very short L_S. However, the contact length between the solidified tube and the mold at high temperature (the part of the transition zone) is large. When the LSI is inside the cooling section (Fig. 9(c)), the heat conduction is mainly along the radial direction, and the bending degree of the LSI is large, which induces a long L_S. The former work of the current authors [7] indicated that the as-cast tube with a high-quality internal surface (R_a = 0.6 μm) could be obtained by HCCM horizontal continuous casting, and the internal surface was little affected by processing parameters. The morphology and roughness of the external surface of BFe10 cast tubes produced by HCCM horizontal continuous casting with different LSI positions are shown in Fig. 10.

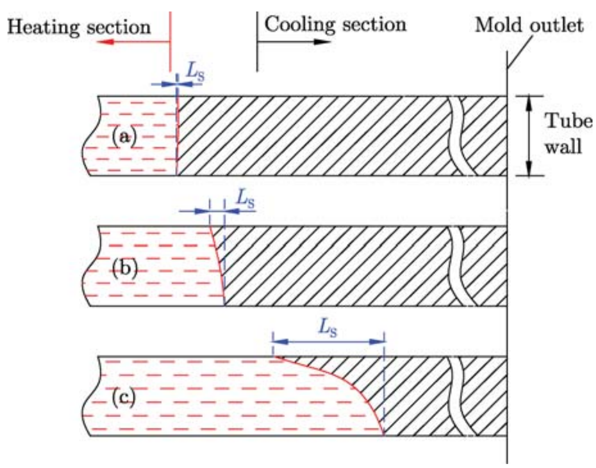


Fig. 9. Schematic diagram of LSI position and shape during HCCM continuous casting: (a) near the heating section exit, (b) middle of the transition zone, and (c) inside the cooling section.

When the LSI is close to the heating section exit ((1)in Fig. 5), longitudinal stripes appear on the surface of the as-cast tube with a poor surface quality and about 7.0 μm surface roughness, as shown in Figs. 10(a) and 10(g), which is due to the straight LSI and the short solidified shell length (L_S), and thus, the solidified tube at high temperature contacts with the internal surface of the mold and the friction between them is great, which induces longitudinal stripes on the external surface of the tube. When the LSI moves toward the mold outlet, e.g., at the middle of the transition zone ((2)in Fig. 5) or near the cooling section entrance ((3) in Fig. 5), although L_S increases in length, the friction between the mold and the tube surface at high temperature decreases remarkably, which tends to produce good surface quality. HCCM horizontal continuous casting could work stably and the as-cast tubes have bright surfaces without macroscopic defects and with a 1.2-1.4 μm roughness, as shown in Figs. 10(b) and 10(c). When the LSI is at the entrance of the cooling section ((4) in Fig. 5), the LSI is greatly affected by the cooling section, and both the bending degree of the LSI and L_S increased. Hence, the radial growth tendency of grains increases and the surface roughness increases to about 2.7 μm, as shown in Figs. 10(d) and 10(g). When the LSI is inside the cooling section ((5) in Fig. 5), L_S is the maximum and the bending degree of the LSI is great, which induces the growth of radial columnar grains and the formation of a long and thin solidified shell. The friction between the solidified shell and the internal surface of the mold at high temperature produces defects, and the roughness increases to about 5.5 μm, as shown in Fig. 10(e). Transverse cracks may stem from the thinner thickness of the tube wall during HCCM horizontal continuous casting, as shown in Fig. 10(f).

The discussion above indicates that the processing parameters have great influences on the LSI position, the LSI shape (solidified shell length), and the contact condition between the tube surface and the internal surface of the mold, which dominates the surface quality of the tube.

Therefore, in order to produce the as-cast tube with a strong axial-columnar-grained microstructure and a good surface quality, the LSI position should be controlled at the middle or nearby region of the transition zone between the heating section and the cooling section, and the temperature gradient should be raised as highly as possible through adjusting the processing parameters. The best processing parameters are as follows: 1250°C melting and holding temperature, 1200-1250°C mold heating temperature, 50-80 mm/min mean drawing speed, and 500-700 L/h cooling water flow rate. Under these conditions, the as-cast tube produced by HCCM horizontal continuous casting has bright internal and external surfaces without macroscopic defects and has a strong axial-columnar-grained microstructure. The surface morphology of the as-cast tube is shown in Fig. 11. The former study [15] by the current authors showed that the tubes produced by HCCM horizontal continuous casting under the conditions above can be directly used for the subsequent cold processing without any internal and external surface treatment.

4. Conclusions

(1) During HCCM horizontal continuous casting, when the LSI is located near the heating section exit, the heat conduction during solidification of the BFe10 tube is mainly along the axial direction, and the microstructure exhibits a strong axial colum-nar grain with the casting texture of {*hkl*}<5$\bar{1}$0>. When the LSI is at the middle of

the transition zone or near the cooling section entrance, the tube still has a strong axial-columnar-grained microstructure ($\{hkl\}\langle 6\bar{2}1\rangle$, $\{hkl\}\langle 2\bar{2}1\rangle$). When the LSI moves to the cooling section entrance or inside the cooling section,

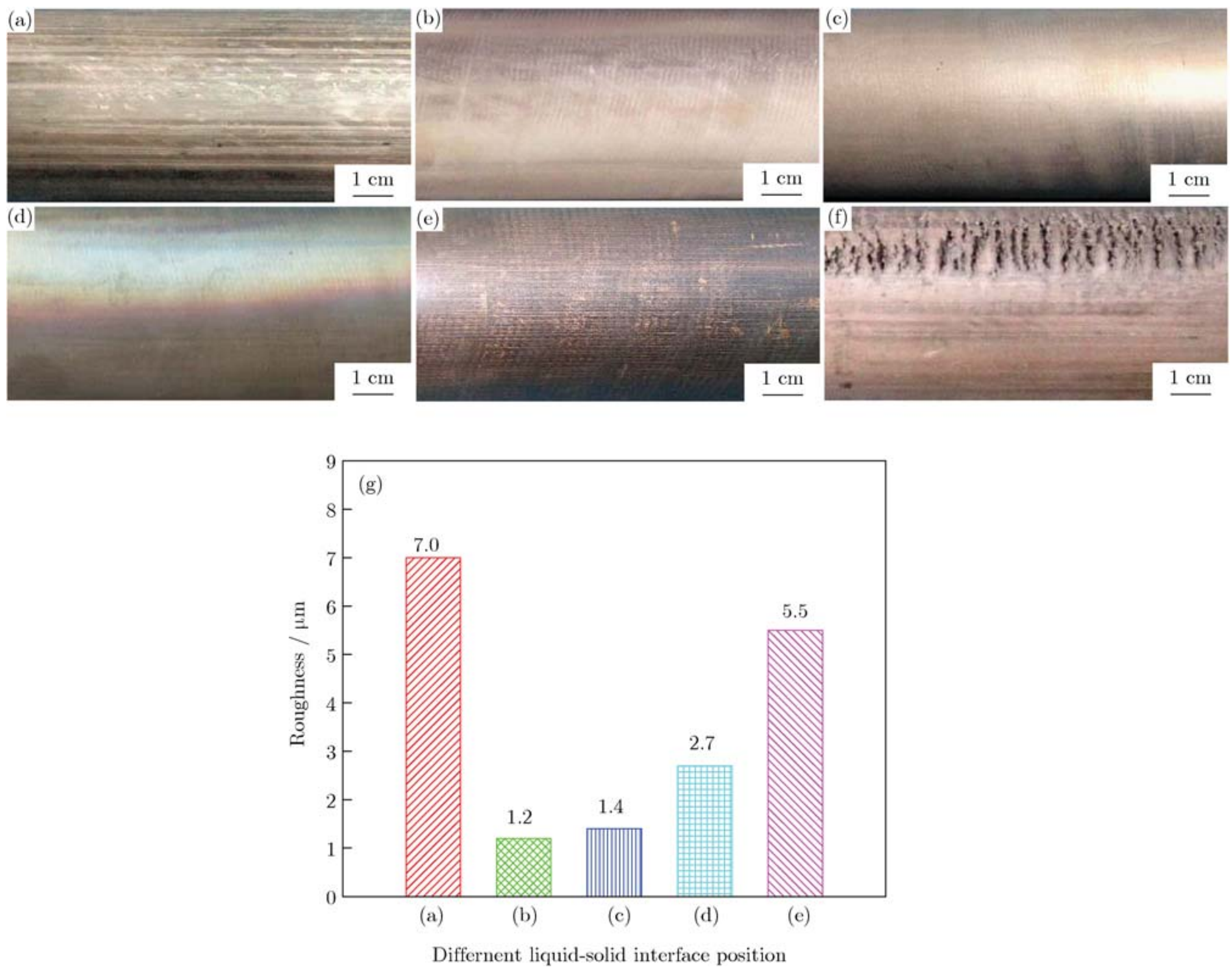


Fig. 10. Surface morphology and roughness of BFe10 cast tubes with different LSI positions: (a) near the heating section exit ((1) in Fig. 5); (b) middle of the transition zone ((2) in Fig. 5); (c) near the cooling section entrance ((3) in Fig. 5); (d) entrance of the cooling section ((4) in Fig. 5); (e) and (f) inside the cooling section ((5) in Fig. 5); (g) surface roughness.

Fig. 11. Surface morphology of BFe10 cast tube with the optimal process parameters: (a) transverse section of the tube and (b) external and internal surfaces of the tube.

the radial heat conduction predominates, leading to a strong radial-columnar-grained microstructure.

(2) During HCCM horizontal continuous casting, the surface quality of the as-cast BFe10 tube is comprehensively affected by the LSI position and shape and the contact condition between the tube and the mold. When the LSI is near the heating section exit, the contact length between the tube and the mold at high temperature is long, and the surface roughness is great (R_a = 7.0 μm). When the LSI is located at the middle of the transition zone or near the cooling section entrance, both the length of the solidified shell and the contact between the tube and the mold at high temperature are short, resulting in the minimum roughness (R_a = 1.2-1.4 μm). When the LSI moves to the cooling section entrance or inside the cooling section, the solidified shell length increases, and the surface quality of the tube falls down to a 2.7-5.5 μm roughness.

(3) Under the conditions of 1250°C melting and holding temperature, 1200-1250°C mold heating temperature, 50-80 mm/min mean drawing speed, and 500-700 L/h cooling water flow rate, the LSI can be controlled within the middle of the transition zone between the heating section and the cooling section of the mold or close to the cooling section entrance. The as-cast BFe10-1-1 tube has a strong axial-columnar-grained microstructure and good surface quality. The elongation of the tube reaches 46.0%-47.2%, and it has bright internal and external surfaces without cracks, scratches, and other macroscopic defects, with a 1.2-1.4 μm roughness. The tubes can be directly used for the subsequent cold-large-strain processing.

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