Heliyon

Received:
14 December 2018
Revised:
15 February 2019
Accepted:
6 March 2019

Cite as: Rensheng Chu, Zhanjun Li, Yong Fan, Jingang Liu, Changwen Ma, Xinhua Wang. Cracking and segregation in high-alloy steel 0.4C1.5Mn2Cr0.35Mo1.5Ni produced by thick continuous casting.
Heliyon 5 (2019) e01329.
doi: 10.1016/j.heliyon.2019.e01329

Cracking and segregation in high-alloy steel 0.4C1.5Mn2Cr0.35Mo1.5Ni produced by thick continuous casting

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Abstract

Based on our innovative application of using thick continuous casting slab 0.4C1.5Mn2Cr0.35Mo1.5Ni (high alloy) for the production of high-quality mould steel, the present study investigated the high cracking susceptibility of high-alloy steel and segregation in continuous casting slab. The thermal expansion and the continuous cooling transformation (CCT) curve measurement, together with a high temperature in situ observation, confirmed the martensite phase transition happening at approximately 583 K that would result in an increase in the hardenability and cracking susceptibility. The cracking susceptibility zone was determined by high-temperature mechanical properties measurement. The high-alloy mould steel has no II brittle zone, and III brittle zone is 973−1148 K. As a conclusion, the straightening temperature should be above 1148 K to avoid the cracking during the continuous casting. Moreover, the elemental segregation of carbon, sulfur, chromium, and molybdenum along the cracking was examined by electron probe microanalysis (EPMA) quantitative analysis that might be another

https://doi.org/10.1016/j.heliyon.2019.e01329

reason for the steel crack formation. It shows that Martensite phase transition happened at approximately 583 K that would result in an increase in the hardenability and cracking susceptibility.

Keywords: Metallurgical engineering

1. Introduction

Nowadays, most of the forgings are produced through mould casting and forging process, especially in the production of high-alloy steels [1, 2, 3, 4]. The high-alloy steels receive mounting attention in the iron and steel industry, due to its high added value in the manufacturing market. However, there are difficulties in the quality control of these steels due to their high carbon and alloy content, and hence high cracking susceptibility [5, 6, 7, 8, 9]. The high quality mould steel is produced after forging, which should qualify via flaw detection, high surface quality, and ±2HRC (Rockwell hardness) difference in hardness uniformity (between the surface and core). It is widely used to the large long-life plastic injection mould, such as home appliances, computer shells, *etc.* The traditional process for high-alloy steels production is electric arc furnace (EAF), ladle furnace (LF) and vacuum decarburization (VD). Then the steel is cast into ingot which used as raw material for mould steel production [10,11]. However, it is not possible to perform the quality check of the steel ingot before the forging process, which caused a high defective ratio of 5−10 % [12,13].

The current cost pressure in mould steel market arises the alternative flow of continuous casting slab to forging process, especially the thick slab. The advantage of using thick continuous casting slab instead of steel ingot is remarkable in decreasing cost and increasing quality rate, realized by the quality check on the slab before the forging process. We could perform the quality control and sulfur print detect to the continuous casting slab, to ensure the quality before forging, which is different from using the ingot (quality check implemented only after forging results in high rejection rate). Moreover, instead of the traditional process, we innovated top and bottom combined blown converter (LD) followed with slab continuous casting (CC) process. However, the LD + CC process is widely used in producing the high-strength low alloy steel, but not the high-alloy steel. Meanwhile, due to the high carbon and alloy content, the segregation and crack control of continuous casting slab is the most significant difficulties [14, 15, 16]. The segregation in the ingot casting is V type, which would be improved by the head and tail cutting of ingot. However, the segregation in the continuous casting slab is center type, which is more serious than ingot. It has a great influence on the quality of product especially after the forging process. People studied the cracking mechanism of the thin continuous casting slab.

https://doi.org/10.1016/j.heliyon.2019.e01329

According to the research of J. K. Brimacombe and Kristiansson [17,18], the different types of internal and surface cracks can form during the continuous casting of steel. Low ductility and cracking in steel is demonstrated by the stresses generated in the solidifying shell. Nakato, H [19] found that the several types of cracks were observed due to the carbon and copper contents.

Many researchers investigated the high-temperature mechanical properties of steels [20]. There is a consensus on the high-temperature brittle zones of steels from the melting point to 873 K [21]. The III brittle zone of steel is in the temperature zone of 873−1173 K. Membranous ferrite and carbonitride precipitated along the austenite grain boundary made the boundary coarsened and caused the brittleness of base matrix. There is a negative relationship between the ductility and the tensile strain rate in the III brittle zone of steel. Many researchers found that the ductility is related to the chemical composition and tensile strain rate. The ductility in these three zones was not always present at the same time, or overlap [22].

However, there are rare study and report on the segregation and crack mechanism of a thick one which is more than 400mm with high carbon and alloy. The present work focuses on the practical process of high-quality mould steel 0.4C1.5Mn2Cr0.35Mo1.5Ni (as shown in Table 1) with our innovated LD + CC process. We try to figure out the segregation and crack mechanism on continuous casting slab with high carbon (>0.3 mass%) and alloy (>5 mass %) content.

2. Experimental

The production process of high-quality mould steel was started from the pretreatment of hot metal, followed with BOF (deoxygenation by aluminum), LF (desulfurization), RH refining (degasification and inclusions removal), calcium treatment (morphology control of inclusions), soft blow, and continuous casting. During the production of high-alloy steels, especially the ones with carbon content above 0.3 mass pct, the high content of carbon and alloy would raise segregation resulting in cracking by an external force. Therefore, it is necessary to study the mechanism of the cracking and find ways to control it.

The thermal expansion curve measurement (DIL402C, NETZSCH, Germany), an illustration of the relationship between expansion and temperature (0−1173 K), is

Table 1. The composition of high-quality mould steel 0.4C1.5Mn2Cr0.35Mo1.5Ni, wt%.

C	Si	Mn	P	S	Cr	Mo	Ni
0.38	0.30	1.50	0.015	0.03	1.0−4.0	0.1−0.8	0.5−3

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used to evaluate the phase transition process to ensure the martensite starting point (Ms) and martensite finishing point (Mf) in low cooling rate for the study of cracking susceptibility. The continuous cooling transformation (CCT) curve measurement (Gleeble2000, DSI, USA), distinct from the thermal expansion curve, examines the phase transition process under different cooling rate to evaluate the cracking susceptibility. The sample was firstly heated from room temperature to 1273 K at a heating rate of 5 K/s, and held for 3 min to ensure a uniform thermal state afterwards, and then quenched to 100 °C with different cooling rate of, 0.1, 0.5, 1, 5, 10, 15, 20, and 30 K/s.

The high-temperature mechanical properties of high-alloy mould steel slab were performed with a thermal simulation test (Gleeble2000, DSI, USA). The diameter of sample is 0.01m and the length is 0.11m. The slab sample was heated to 1623 K, and then cooling down after 5 min holding with a rate of 3 K/s. When temperature reached to the experimental temperature (973, 998, 1023, 1048, 1073, 1098, 1123, 1148, 1173, 1198, 1223, 1248, 1273, 1323, 1373, 1423, 1473, 1523, 1573, and 1623 K) and held for 2 min, the sample was going through a tensile test with a strain rate of 1×10^{-3}/s. After the sample broken down, speciments were quenched with water to ensure an original microstructure and morphology state. The contraction of cross-sectional area was measured and analyzed with time and loads. The solidification characteristic curve was also figured out with the thermal simulation test, to investigate the mechanical property of steels from low to high temperature (573−1973 K) section. The average value was acquired by at least three samples.

The high temperature in situ observation was performed with a confocal laser scanning microscopy (CSLM, VL2000DX-SVF17SP, Lasertech, Japan) to inspect the morphology during the cooing of slab, and also examine the thermal expansion and CCT curve. The sample was heated up to 1473 K firstly, held 5 min, and then cooled down with a rate of 8, 12, and 15 K/s.

The microhardness was measured by a microhardness tester (Vickers hardness, VTD512, Wowei, China). Each sample was measured on and took the average of three points at 2 mm interval. This experiment could perform in segregation, non-segregation area and a transition area of the sample (the continuous casting slab after forging).

Because the in-situ segregation detection could only provide the overall segregation image in a large area, the small area segregation detection was realized by scanning electron microscope and energy dispersive spectrometer (SEM-EDS, S3400N, Hitachi, Japan) and electron probe microanalysis (EPMA, JXA-8530F, Jeol, Japan) to study the mechanism of cracking. The measurements were loaded with sample obtained in the same width direction of the slab.

https://doi.org/10.1016/j.heliyon.2019.e01329

3. Results and discussion

3.1. Phase transition

The thermal expansion curve and CCT curve were used to analyze the phase transition and cracking susceptibility of continuous casting slab for production of high-alloy steels. The thermal expansion curve was measured at a slow cooling rate less than 0.1 K/s, while the CCT curve was figured co-related with practical cooling condition above 0.1 K/s. These two experiments together would provide overall information on the cracking susceptibility.

As shown in Fig. 1 which is the thermal expansion curve of high-alloy mould steel slab, the black line is the heating curve, and the blue one is cooling curve. These results are the phase transition during cooling. In the CCT curve of high-alloy mould steel, the temperature at which pearlite transforms to austenite (Ac1) and the final temperature at which all the ferrite is converted to austenite (Ac3) were 1002 K and 1076 K, and the starting temperature of the transformation of austenite to pearlite during cooling (Ar1) and the critical temperature line of ferrite precipitated from austenite during cooling (Ar3) were 562 K and 672 K, respectively. During the cooling process, there was only martensite transformation without bainite transformation. The Ar1 and Ar3 were low resulting in increasing the hardenability and cracking susceptibility.

The CCT curves of high-alloy mould steel slab at different cooling rates were shown in Fig. 2. The area between red and green solid lines is the phase transition area. The high-alloy mould steel contains mainly bainite and martensite when the cooling rate less than 0.5 K/s. The martensite domain started from623−673 K and ended at

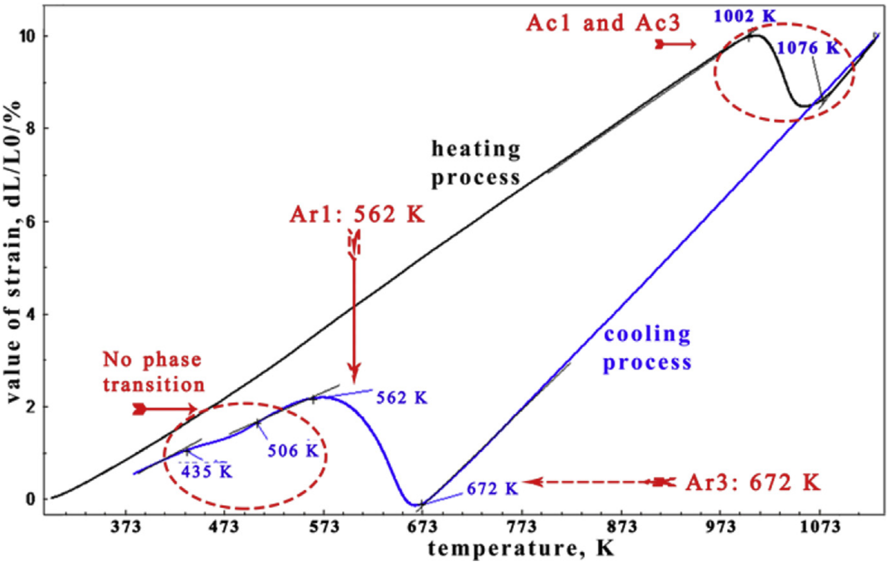

Fig. 1. The thermal expansion curve of high-alloy mould steel slab.

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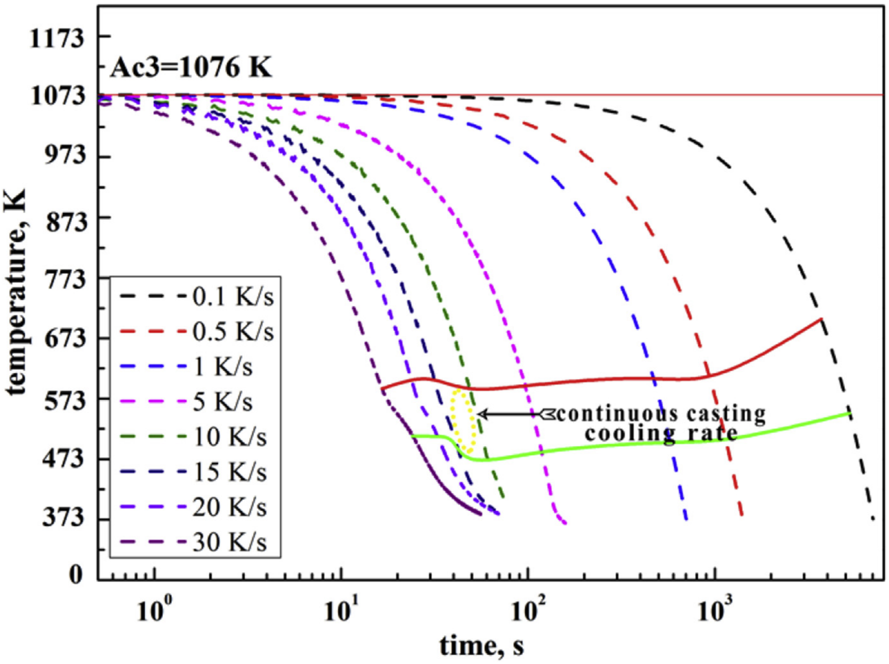

Fig. 2. The CCT curves of high-alloy mould steel slab at different cooling rates.

513−528 K when the cooling rate is above 0.5 K/s. The martensite transformation region was vast, as shown in the CCT curve, and the critical cooling rate was between 0.1−0.5 K/s. Generally, in the practical continuous casting process, the cooling rate is within 10−15 K/s (the average cooling rate of caster mold), under which the steels contains mainly martensite, resulting in increasing the hardenability and cracking susceptibility.

With the use of a confocal laser scanning microscopy (CSLM), the high temperature in situ observation was performed and shown in Fig. 3. The photos in the horizontal direction is the phase transition under the same cooling condition, but different temperature. The first one is the time and temperature about to happen the phase transition. The second and third ones are the status of being and after finishing the phase transition. The same phenomenon was observed that martensite phase transition happened at approximately 583 K at the cooling rate of 8, 10, 12 K/s respectively. This experiment makes it clear that the structural transformation of high-alloy steel is within low temperature zone. This temperature zone is the temperature of the continuous casting slab out of caster. Due to the high cracking susceptibility of the martensite phase [23], slow cooling control or cold heap control is required to avoid the appearance of cracking during the continuous casting process.

3.2. High-temperature mechanical properties

There is a close relationship between the surface/inner cracking of continuous casting slab and the high-temperature mechanical properties of slab. Moreover, the

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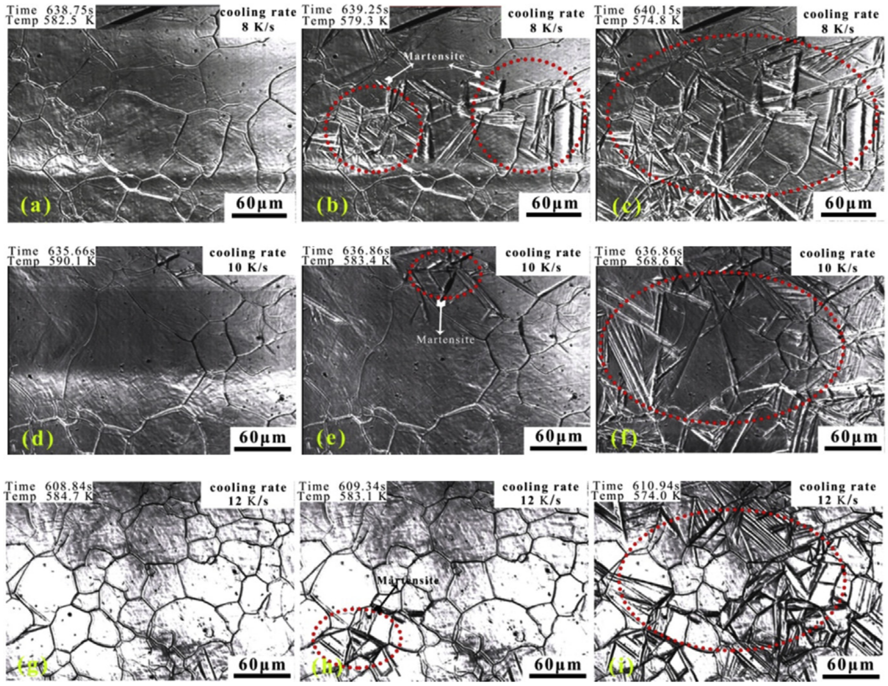

Fig. 3. The high temperature in situ observation of mould steel slab (a∼c: the phase transition at the cooling rate 8 K/s; d∼f: the phase transition at the cooling rate 10 K/s; g∼i: the phase transition at the cooling rate 12 K/s).

high-temperature ductility of the slab is fundamental in configuring the secondary cooling system. Therefore, in order to avoid the surface/inner cracking and design a better secondary cooling process, it is necessary to study the high-temperature mechanical properties of slab. Unfortunately, there is rare report on the high-temperature ductility of high-alloy steel, which has a high carbon content, such as mould steel.

Fig. 4 shows the tensile strength of high-alloy mould steel slab between 973−1623 K. It could be concluded that the tensile strength is decreasing along with the temperature increase. The tensile strength remains shallow and gentle gradient when the temperature is above 1273 K.

Fig. 5 shows the contraction of cross-sectional area (RA) of high-alloy mould steel in different temperature. RA increases from 57.6 % in 1623 K, to 86 % in 1473 K. The samples show good ductility between 1198−1523K, and the RAs are above approximately 70 %, reaching to 89 %. The RA decreases along with the temperature, when the temperature is lower than 1323 K. Mintz. etc [20] have observed the increase of continuous slab surface cracking when the RA is less than 40%. So, the RA value of 40 % was set as a criterion to evaluate the brittleness. From our results, the III brittle zone of high-alloy mould steel was 973−1148 K, which is also the cracking susceptibility zone suggesting the low ductility of slab. Moreover,

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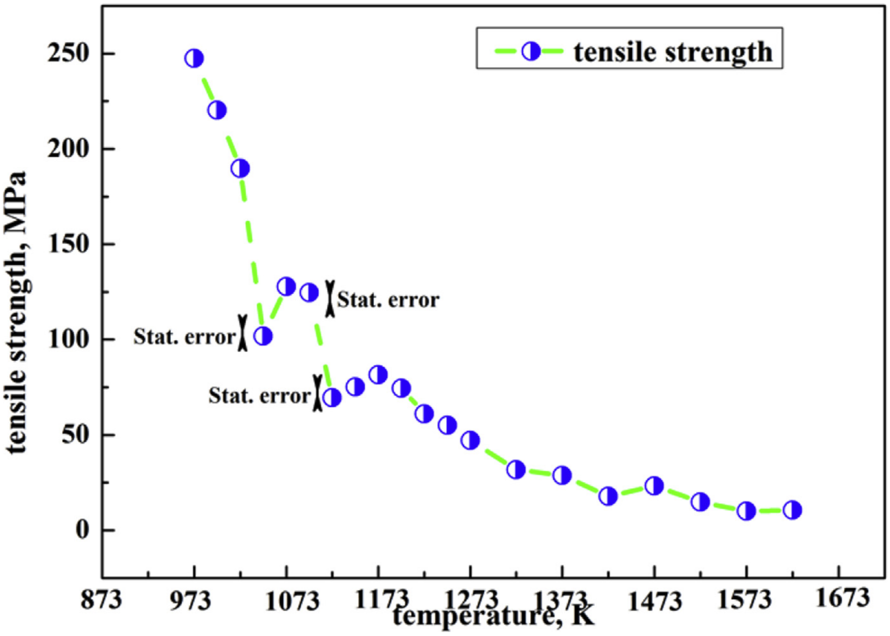

Fig. 4. The tensile strength of high-alloy mould steel slab.

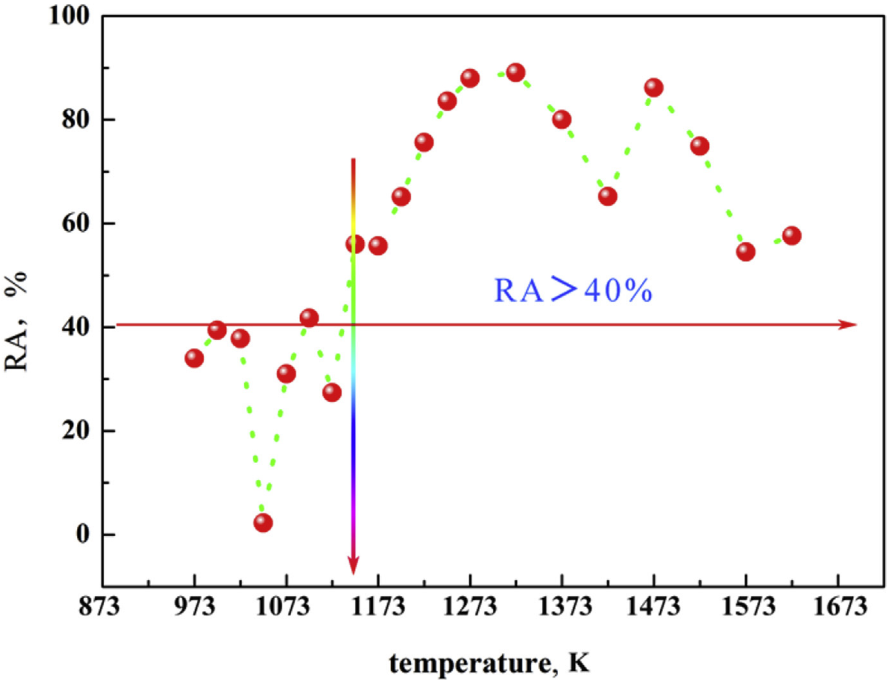

Fig. 5. The contraction of the cross-sectional area of high-alloy mould steel slab.

due to the high carbon content, there was no II brittle zone, which is distinctive with other high-strength steel with low alloy content. As a conclusion, the straightening temperature should be above 1148 K to avoid the cracking in slab during the continuous casting.

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3.3. Segregation and cracking susceptibility

In general, severe segregation in steel would turn into hard phase structure, which would generate cracking during the forging process. The hardness of segregation and regular structure in high-alloy mould steel was shown in Fig. 6. Position 1−3 are lines containing three points from one quarter to the center on the slab. From our measurement, the segregation structure was hard phase structure (370−380 HV), and the regular ones were soft phase structure (170−180 HV). These two structures had a significant difference in the hardness which was the reason for cracking during the forging process.

Because the in-situ segregation detection could only provide the overall segregation image in a large area, the small area segregation detection was realized by electron probe microanalysis as shown in Fig. 7. It could be concluded that carbon, chromium, molybdenum, phosphorus, and sulfur concentrated along the cracking, which resulted in the hard phase structure due to the segregation.

Fig. 8 and Table 2 show the EPMA line scan and quantitative analysis of cracking. The minimum values are equivalently same as the base material, which listed here for a comparison. There were obvious high concentration of carbon (0.28−1.80 mass%), sulphur (0.01−1.73 mass%), chromium (1.26−8.14 mass%), and molybdenum (0.12−0.61 mass%). This segregation phenomenon was attributed to the selecting crystallization and dendrite solidification of steel. The center segregation could not be avoided due to the solute accumulation in the final solidification. These

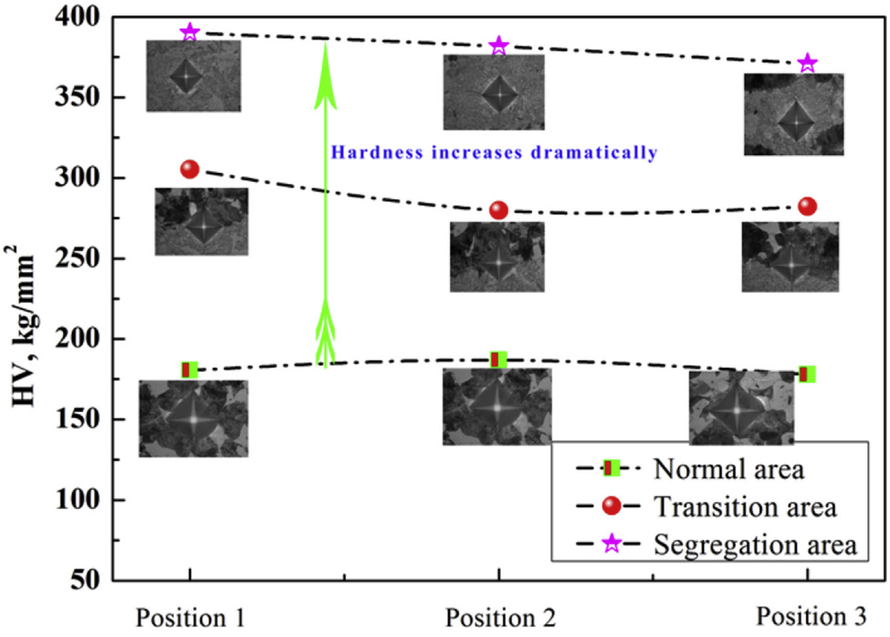

Fig. 6. The hardness of segregation and regular structure in high-alloy mould steel after forging.

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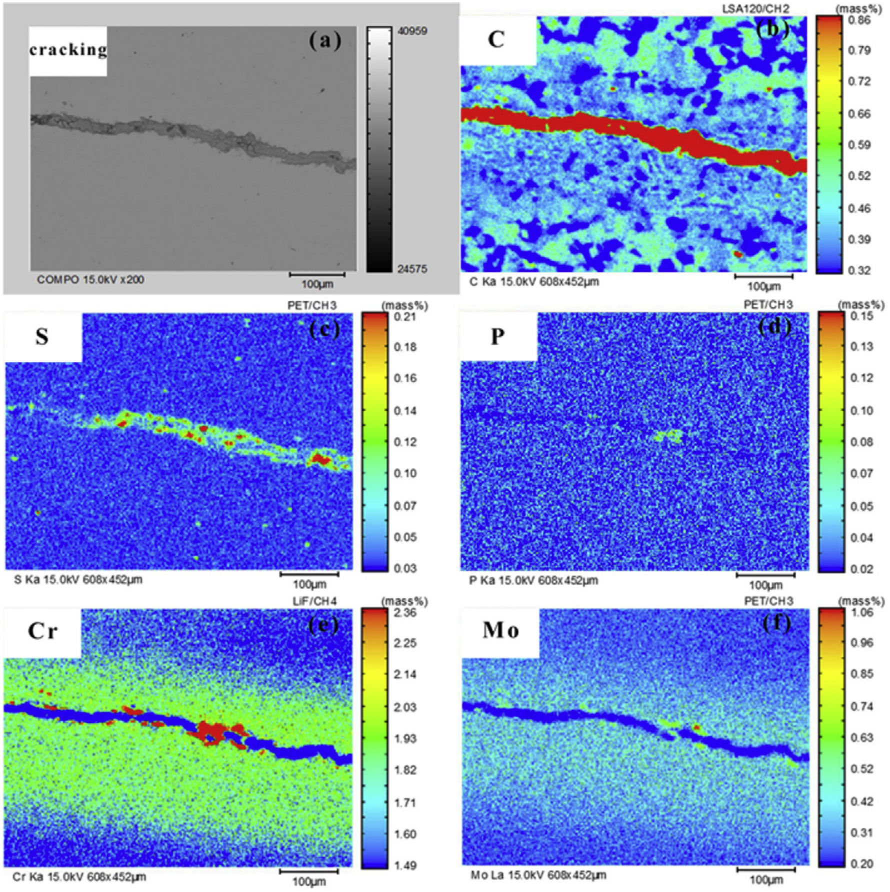

Fig. 7. EPMA mapping of elemental segregation of cracking in high-alloy mould steel (a: morphology of cracking; b: C segregation; c: S segregation; d: P segregation; e: Cr segregation; f: Mo segregation).

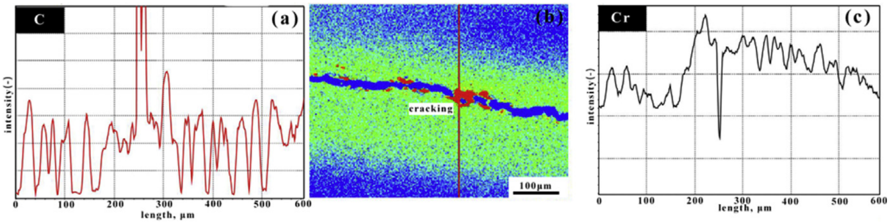

Fig. 8. EPMA line scan of cracking in high-alloy mould steel (a: C segregation; b: scan of cracking; c: Cr segregation).

concentrations are all higher than the base matrix to form the hard phase structure in steel thermodynamically easily.

3.4. Solidification

It was already known that the high-alloy steel with high carbon content has a high cracking susceptibility. Moreover, the segregation was another difficulty in forging

Table 2. EPMA quantitative analysis of different elements of cracking in high-alloy mould steel.

Element	Max, mass%	Min, mass%	Average, mass%
C	1.80	0.28	0.51
P	0.08	0.00	0.03
S	1.73	0.01	0.06
Cr	8.14	1.26	1.90
Mo	0.61	0.12	0.31

production with continuous casting slab. Therefore, in the practical process, an improvement should be applied to the continuous casting process. The solidification characteristic curve measurement is necessary to optimize the process.

The production process of high-strength steel with low alloy content is mature, and many steel species such as ship steel D36 and pipeline steel X65 were successfully manufactured. We tried to produce the high-alloy mould steel based on the optimizing of current mature technology.

From the solidification characteristic curve of high-strength steel with low alloy content (D36 and X65) and high-alloy mould steel as shown in Fig. 9, the solidification contraction of the high-alloy steel was less than that of low-alloy steel below liquidus and solidus point. This information suggests the improvement of mould taper ensure

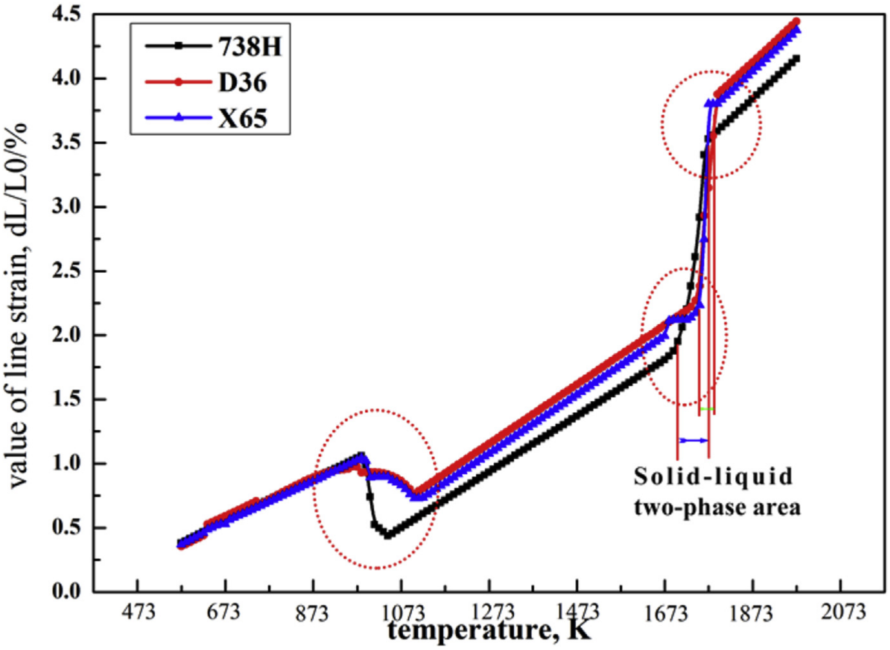

Fig. 9. The solidification characteristic curve of high-strength steel with low alloy content (D36 and X65) and high-alloy mould steel slab.

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the strength of primary slab shell. Moreover, the solidus point of high-alloy steel was less compared with low-alloy steel, and their liquid-solid phase temperature range was different (high-alloy steel ≥353 K, low-alloy steel 278−338 K). Therefore, during continuous casting, the strength of primary slab shell would be low.

Due to the high cracking susceptibility of high-alloy steel and segregation in continuous casting slab, it is required to optimize the slow cooling and soft reduction process in continuous casting to reduce the segregation and cracking.

4. Conclusions

(1) Martensite phase transition happened at approximately 583 K that would result in an increase in the hardenability and cracking susceptibility

(2) The high-alloy mould steel has no II brittle zone, and III brittle zone is 973−1148 K. As a conclusion, the straightening temperature should be above 1148 K to avoid the cracking during the continuous casting.

(3) The elements segregation of carbon, sulfur, chromium, and molybdenum was observed along the cracking that might be another reason for the steel crack formation.

Declarations

Author contribution statement

Yong Fan: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Rensheng Chu: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Jingang Liu & Changwen Ma: Conceived and designed the experiments; Performed the experiments.

Zhanjun Li: Performed the experiments.

Xinhua Wang: Contributed reagents, materials, analysis tools or data.

Funding statement

This work was supported by the Japan Society for the Promotion of Science (JSPS) and Alexander von Humboldt (AvH) Foundation.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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