EFFECT OF ULTRA-FAST COOLING ON MICROSTRUCTURE AND PROPERTIES OF HIGH STRENGTH STEEL FOR SHIPBUILDING

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Abstract

The effect of ultra-fast cooling(UFC) and conventional accelerated cooling(AcC) on the mechanical properties and microstructure of controlled rolled AH32 grade steel plates on industrial scale were compared using tensile test, Charpy impact test, welding thermal simulation, and microscopic analysis. The results show that the properties of the plate produced by UFC are improved considerably comparing to that by AcC. The yield strength is increased with 54 MPa without deterioration in the ductility and the impact energy is improved to more than 260 J at -60 ℃ with much lower ductile-to-brittle transition temperature(DBTT). The ferrite grain size is refined to ASTM No. 11.5 in the UFC steel with uniform microstructure throughout the thickness direction, while that of the AcC steel is ASTM No. 9.5. The analysis of nucleation kinetics of α-ferrite indicates that the microstructure is refined due to the increased nucleation rate of α-ferrite by much lower γ→α transition temperature through the UFC process. The Hall-Petch effect is quantified for the improvement of the strength and toughness of the UFC steel attributed to the grain refinement.

Introduction

The most important of TMCP technology will enhance microstructure refinement. The effect of CR on ferrite nucleation rate is increased at the temperature range of austenite non-recrystallization[1]. It is a key technology progress of industrial can improve both strength and toughness of HSLA steels by the more efficient and low cost way of refine ferrite grain[2]. Although use heating temperature control, adding Nb to improve the austenite recrystallization temperature and low temperature heavy reduction rate of the TMCP process. But the minimum limit of grain size of C-Mn steel is produced by conventional TMCP reach to 5 ~10 μm, meanwhile Nb and other alloy are widely consumed.

According to the deficiency of conventional TMCP, Belgian(CRM), Japan(JEF) and china(RAL) developed the UFC system, It has been applied to medium and heavy plate production line of domestic and external.

In this paper, the influence of the ultra fast cooling process and the traditional rapid cooling process on the microstructure and properties of high strength ship steel is studied.

Experimental procedure

Table 1 shows the required actual chemical composition of the AH32 grade Nb-Ti microalloy plate steels, which were supplied by Ansteel Corp., China. The steel was melted in a 90 ton oxygen blown converter. The 230mm thick slab was rolled into plate. It is a typical chemical composition of high strength ship plate steel of AH32 grade.

Table 1 Composition of steel (mass fraction,%)

C	Si	Mn	P	S	Nb	Ti	Als	C_{eq}
0.12	0.15	1.21	0.017	0.002	0.035	0.006	0.03	0.33

Ceq=C+Mn/6+(Cr+V+Mo)/5+(Cu+Ni)/15

Steel A and B are heated to 1150～1200 ℃ for heat preservation for 300 minutes, then they are used to high pressure water descaling. By controlled rolling in austenite recrystallization and non-recrystallization region combining with different controlled cooling technology can attain the thickness of 30mm. Steel A used UFC cooling process and Steel B used AcC cooling process, the concrete parameter of TMCP are presented in Table 2.

Table 2 Rolling and cooling parameter of steel (℃)

Steel	Start rolling of 1st stage	Start rolling of 2nd stage	Final rolling	Start cooling temperature	Final cooling temperature	Cooling method
A	1050	900	850	795	560	UFC
B	1050	850	810	760	630	AcC

According to the provisions of the national standard GB/T 2975, GB/T 228.1 and GB/T 229. Tensile, impact testing, and optical microscopy were used in this study. The tensile direction of the tensile specimens was vertical to the rolling direction and the lengthwise of Charpy impact specimens was parallel to the rolling direction of the plates. Standard Charpy impact test was carried out at various temperatures on a standard Charpy impact-testing machine. Metallographic specimens were received in the middle of rolled samples with the rolled surface. Use ZEISS Axiovert200 MAT and FEI QUANTA 400 imagine analysis and linear intercept technique after etching in 4% nital were used for grain size measurements.

Experimental Results

Mechanical Properties

The mechanical properties including yield strength, tensile strength, elongation, and CVN impact energies measured at -40℃ are given in Table 3. These data were compared with mechanical properties in the rules of Classification Society. It is observed that the yield strength of steel A is 54MPa higher than steel B, tensile strength of steel A is 36MPa higher than steel B. This shows that UFC can significantly improve yield strength and keep the elongation unchanged. UFC technology on the impact toughness of the steel is improved more significantly are shown in Figure 1. The results show that although steel A and steel B meet the requirements of EH40 standard, steel A has more excellent mechanical properties.

Table 3Tensile and impact energy of Steel A and Steel B comparing with requirements for EH36 and EH40

Steel	Yield Strength /MPa	Tensile Strength /MPa	Elongation /%	Mean impact energy at -40 ℃ /J	
				Transverse	Longitudinal
Steel A	466	568	29	273	280
Steel B	412	532	28	69	170
EH36	≥355	490~630	≥21	≥24	≥34
EH40	≥390	510~660	≥20	≥26	≥39

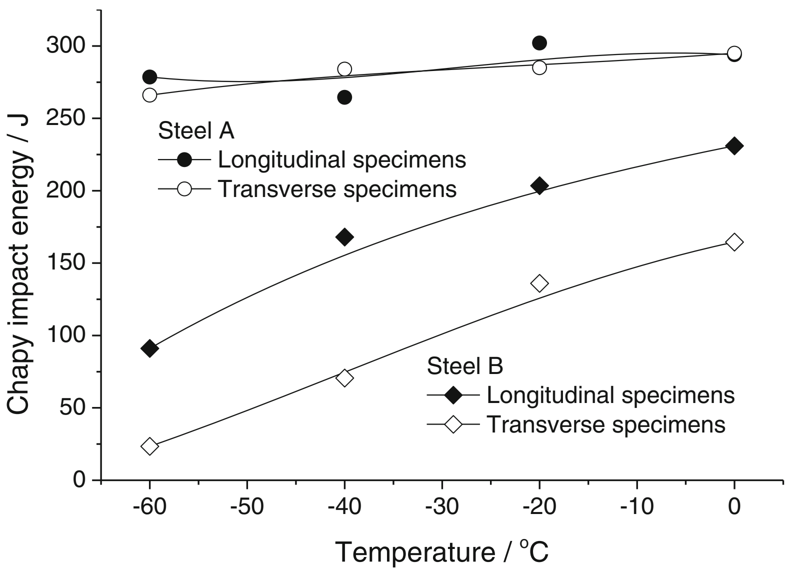

Fig.1 Charpy impact energy curves of longitudinal and transverse specimens of steel A and steel B

Microstructure

The results of microstructure characterization are shown in Figs. 2 and 3. The microstructures of steel A consisted of polygonal ferrite, acicular ferrite, granular bainite and pearlite, the average grain size was 5~10 μm, the grain fineness is 11～12 grade; The microstructures of steel B consisted of polygonal ferrite and pearlite, the average grain size was 15~25 μm, the grain fineness is 9~10 grade. The comparison of steel A and steel B on grain size distribution difference are shown in Figure 4. The comparison shows that steel A has small and uniform grain size, the difference of grain size on direction of thickness is small; steel B show an uneven distribution and very difference grain size. Figures 5(a) and 5(b) are SEM micrographs of steel

A and steel B. It can be seen from figure 5(a) that morphology features of granular bainite and acicular ferrite are changed from austenite transformation, the ferrite volume fraction is about 78%. Figure5(b) show that the magnitude of pearlite of steel B are about 20nm, the ferrite volume fraction is about 85.5%. ferrite and pearlite can be fully grown by low cooling rate.

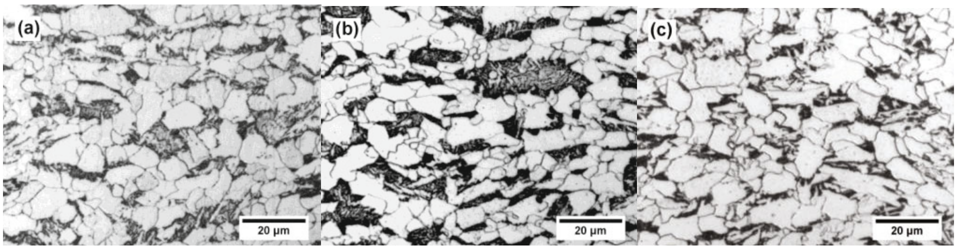

Fig.2 Microstructure of the steel A at (a) subsurface, (b) quarter-thickness and (c) middle-thickness

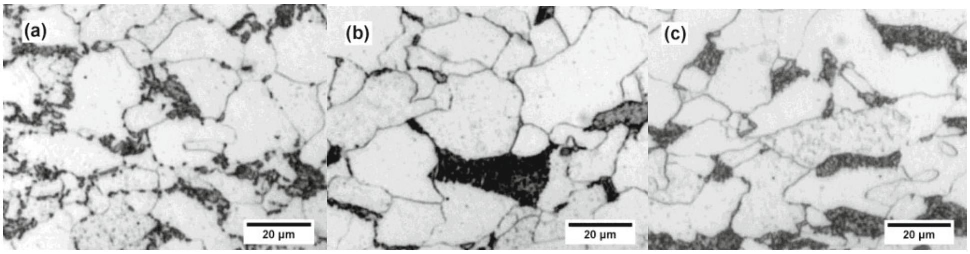

Fig.3 Microstructure of steel B at (a) subsurface, (b) quarter-thickness and(c) middle-thickness

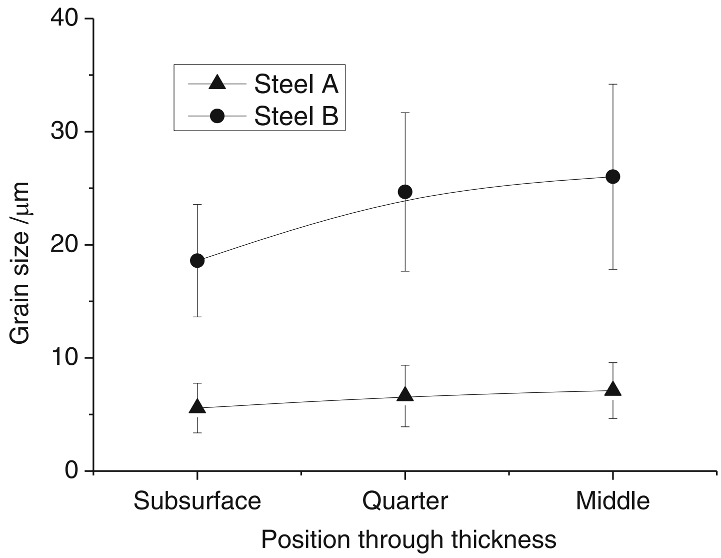

Fig.4 Comparison of grain size of steel A and steel B through thickness

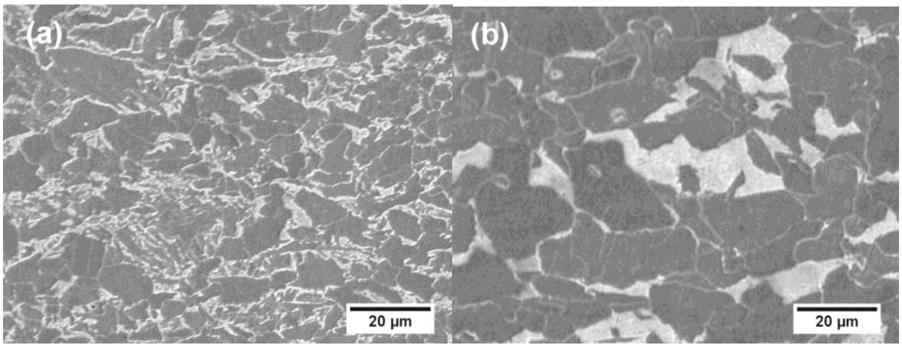

Fig.5 SEM micrographs of steel A and steel B

Analysis and Discussion

$\gamma \rightarrow \alpha$ transformation is happening in the process of cooling after rolling. It has been found that grain boundary and dislocation promotes nucleating and growing of α[9]. Work hardening during deformation of austenite at the temperature range of austenite non-recrystallization, which formed deformation band with high density dislocation and increase nucleation ratio, then the grain refinement can be realized by rolling at non-recrystallization zone. With the increase of undercooling, the driving force for free energy is enhanced. which can effectively refining the growing of austenite grains[1]. ferrite grain size can be calculated by formula (1)[9]. $S_v(p)$ is the interface area of unit volume. $I_s(p)$ is the nucleation rate of unit area. $\alpha(p)$ is parabolic rate constant. $\sqrt{I_s(p)}/\alpha(p)$ is the function of transition temperature and press quantity. The lower of transition temperature, the finer of austenite grains. The cooling rate of steeel A was significantly higher than that of steel B, $\sqrt{I_s(p)}/\alpha(p)$ were significant figures, that is austenite grain size is significantly smaller than the steel B.

$$D_\alpha = \left(\frac{S_v(p)}{2\sqrt{2}} \frac{\sqrt{I_s(p)}}{\alpha(p)} \right)^{-1/3} \qquad (1)$$

Figure 6 show that CCT curve of steel A and steel B. Steel A can be formed fine ferrite and bainite at UFC process. Using UFC not only increases the rate of nucleation of ferrite but hinder grain growth. With the slow cooling rate of steel B, the lower nucleation rate of ferrite and the higher growth rate of grain.

The microstructure grain size determines the property of steel,the relationship between strength and grain size can be expressed by Hall-Petch formula (2)[10].

$$\sigma_y = \sigma_i + \sum k_i \cdot c_i + k_y d^{-1/2} \qquad (2)$$

σ_y is yield strength, σ_i is friction stress, c_i is solid solution elements, k_i is solid solution strengthening factor, k_y is the grain size of the enhancement factor, d is grain size. k_y= 21.9 MPa mm$^{1/2}$[10], According to calculation, the grain refinement improves the strength of 67.6MPa, the results is approximate to the actual measured yield strength. That means the increase of strength and toughness are mainly due to grain refinement. Pickering summed up the relation of ductile-brittle transition temperature (ITT) and austenite grain size, such as furmula (3)[10]. The result of formula (3) can be calculated is correspond to figure 1.

$$ITT(℃) = 19 + 44(\%Si) + 700(N_f)^{1/2} + 2.2(\%Pearlite) - 11.5d^{-1/2} \quad (3)$$

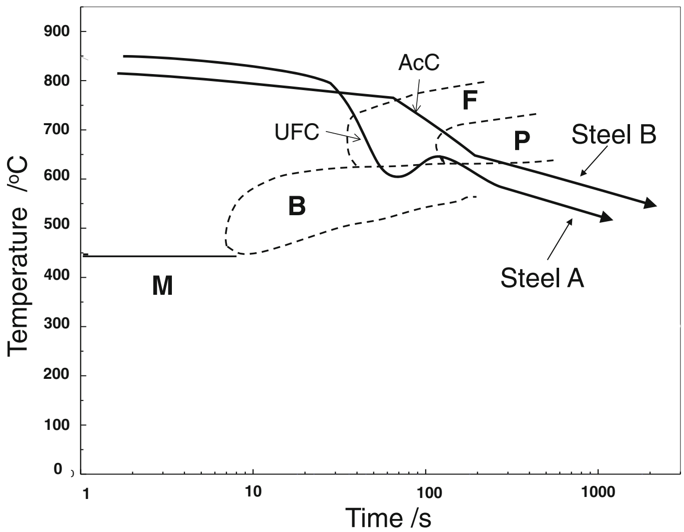

Fig.6 The schematic diagram of the cooling path of steel A and steel B superimposed on CCT diagram of AH32.

Conclusion

Using UFC process greatly refine the microstructure and improves the uniformity in the thickness direction, the ferrite grain reach to 11.5 grade comparing with that of AcC process. Using UFC technology to make the yield strength increased by 54 MPa, the impact energy increased by more than 100 J for -40 ℃, the ductile to brittle transition temperature of steel is decreased. UFC process reduces the austenite transition temperature and improve the ferrite nucleation rate. It significantly refines the ferrite grain and improve strength and toughness of steel.

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