Advances in Engineering, volume 100
International Conference on Manufacturing Engineering and Intelligent Materials (ICMEIM 2017)

Gradually Changing Surface Microstructure and Impact Resistance of Hot Formed 10CrNi3MoV Marine Steel

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Keywords：High Strength Marine Steel; Hot Forming; Microstructure; Iimpact Resistance

Abstract: Microstructural changes of 10CrNi3MoV marine steel before and after hot forming were detected by testing devices such as X-ray diffractometer, the formation causes and law of gradually changing surface microstructure of hot-formed material and those of the interior martensite structure were analyzed. The study shows that the gradually changing surface microstructure formed in 10CrNi3MoV marine steel after hot forming makes the material hardness increases sharply from surface to interior within the 0-0.25mm surface depth scope, and the hardness is maintained at 40-45HRC after reaching the 0.25mm depth; the material malleability decreases evidently from surface to interior within the 0-0.25mm surface depth scope, with the change amplitude being great, and the decrease amplitude is obviously reduced at the 0.25-0.50mm depth scope, and becomes very small after the 0.50mm depth is reached; the role of its gradually changing surface microstructure and the display of large malleability characteristic by the soft outer layer prevent the interior high-strength martensite from premature failure in the impact process, and enable a gentle structural peak value, and the gentle impact level and the gradual failure of the material enable the structure to keep a high energy absorption capacity and impact resistance. This indicates that hot-formed 10CrNi3MoV marine steel combines the excellent properties of single-phase materials, and is suitable for structural members that should withstand impact and absorb energy.

Introduction

The swift development of shipping industry is setting increasingly higher requirements on shipbuilding, and the application of high strength marine steel has become an effective way to improve shipbuilding quality. In the early period, high strength marine steel was only used in the deck and bottom of very large crude oil carriers (VLCC) , but now, it gains a wide application in large oil carriers, VLCC and other large ships, becoming a good material used more and more widely in modern shipbuilding industry[1]. However, such technical bottleneck problems as difficult forming and easy-to-generate forming defects greatly restrict the application of high strength marine steel in shipbuilding. Hot forming technology can not only well solve the bottleneck problems such as difficult forming of high strength ship still but also obtain formed parts with ultra-high performances [2]. Extensive research has been made on the hot forming technology of high strength steel by both foreign and domestic scholars, which mainly concentrate on hot forming process, numerical simulation and hot forming experiment, etc. For example, Eriksson and Oldenburg [3] carried out the experimental research on the temperature and strain rate correlation of high temperature forming material; Bergman and Oldenburg [4] made numerical simulation on stamping process; Naderi and Merklein [5,6] studied the flowing principle and material parameters of hot forming of boron steel at high temperature, respectively; Ma Ning et al. [7] studied the high strength boron steel hot forming technology and application; and Xing Zhongwen et al. [8] carried out experimental research on hot stamping of boron steel. These efforts are references for the research of hot forming technology of high strength marine steel.

The early period research of the project shows that, in the hot forming of high strength marine steel, the high temperature oxidation and de-carbonization of the surface layer of hot-formed material due to the interaction between sharp heating and temperature reduction can lead to the changes in the material surface and interior microstructures. Such microstructural changes can have a great impact on the performances of the hot-formed materials, and the gradually changing microstructure thus formed will greatly affect the hot forming process of high strength steel plate and its mechanical properties after hot forming [9-11]. At present, foreign and domestic research efforts in this aspect have been rarely reported. This paper describes the research on the microstructural changes of hot-formed 10CrNi3MoV marine steel and the impact resistance of high strength marine steel after hot forming, and the establishment of the related theory, thereby providing reference to the application of hot forming technology for high strength marine steel.

Test Design

Design of Hot Forming Test

Hot forming is a forming technology comprising heating 10CrNi3MoV marine steel to austenitizing temperature, forming it by stamping at high temperature, cooling it in the die of cooling system for martensitic phase transformation to obtain the required shape under the condition of guaranteeing the original high strength of material, and quick quenching to get a formed piece with ultra-high strength. The hot forming process parameters are described as follows: the die is preheated before stamping and the 10CrNi3MoV marine steel is heated in a mid-frequency induction heating furnace to its austenitizing temperature (about 930℃-950℃); the temperature holding time is 5min, the cooling speed is greater than 50.0℃/s, the pressure holding time is about 10s, the temperature control scope of the die cooling system is 20℃-220℃, the workpiece is taken out at a temperature of 120℃-180℃, the time of the whole stamping process is 15s-20s and the stamping speed is 10mm/s.

Test Material

10CrNi3MoV marine steel with a plate thickness of 12mm, whose chemical composition and mechanical properties are shown in Tables 1 and 2[12]

Table 1 Chemical Composition of 10CrNi3MoV Marine steel

C	Si	Mn	S	P
0.07-0.14	0.17-0.37	0.30-0.60	≤0.015	≤0.020
Ni	Cr	Mo	V	
2.60-3.00	0.90-1.20	0.20-0.27	0.04-0.10	

Table 2 Mechanical Properties of 10CrNi3MoV Marine Steel

Yield strength δ_s /MPa	Tensile strength δ_b /MPa	Elongation percentage δ /%	Contraction percentage of area ψ %	Impact power AK(-20 ℃)(V model)/J
590～745	670～850	≥16	≥50	≥80

Test Process

1) Determination of metallographic structure: The structure and surface morphology of hot-formed 10CrNi3MoV marine steel were observed and determined by using a KYKY-2800B SEM, an XRD-7000S X-ray diffractometer and an EDAX EDS, and the chemical composition change was analyzed by the EDS (discussed in another paper).

2) Hardness determination: An MH-5 micro-hardness tester was used, with a load mass of 20g and a loading time of 10s.

3) Static bending test: DNS300 electronic universal testing machine was used, with a loading speed of 20mm/min and placement of 154mm.

4) Impact resistance determination: A JBGD-300W impact tester with a punch mass of 50kg and a dynamic loading at a punching rate of 50km/h was used to test the impact resistance of 12mm 10CrNi3MoV marine steel before and after hot forming, and numerical simulation was also made.

Microstructure of Hot-formed Material

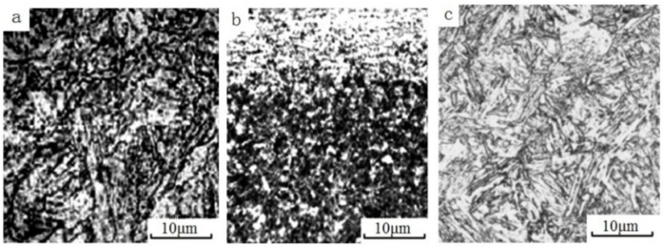

Fig. 1 Microstructures of 10CrNi3MoV before and after hot forming

The microstructures of 10CrNi3MoV marine steel before and after hot forming are as shown in Fig. 1. Fig. 1a is the microstructure of 10CrNi3MoV marine steel before hot forming. It can be seen from the figure that this microstructure is mainly of ferrite-sorbite mixed microstructure, there are fine carbide particles uniformly distributed on the ferrite matrix, the carbides have clear appearance, and the lath direction does not fully disappear. According to the micro-morphological characteristics, it can be affirmed that the sorbite of 10CrNi3MoV marine steel before hot forming is of tempered sorbite structure with martensitic direction characteristic.

In hot forming of 10CrNi3MoV marine steel, at first, the material temperature rose rapidly, when the material was heated to the austenite temperature, the tempered sorbite structure with martensitic direction characteristic was transformed into austenite structure. The quicker the heating speed and the greater the overheating was, the higher the nucleation rate of austenite crystal nucleus and the finer the crystals would be. When the material was heated to the austenite temperature and kept at this temperature, uniform austenite was obtained. In this process, the mechanical properties of the material underwent a radical change, i.e. sharp decrease of strength and hardness and obvious increase of plasticity, facilitating the forming process. After that, the 10CrNi3MoV marine steel was quickly formed and cooled at a maintained pressure, and the material temperature sharply decreased; when the austenite obtained after heating and temperature holding was cooled to below the critical point A1, it become overcooled austenite in an unsteady state. When the overcooled austenite was cooled to the ambient temperature at an extremely speed, the oversaturated solid solution of carbon in α -Fe ——martensite was formed. The greater the cooling speed and the greater the overcooling degree was, the quicker the overcooled austenite was turned into martensite.

Generally, in the hot forming of material, there is a continuously changing temperature field. Under the role of this temperature field, the plate microstructure and mechanical properties will change, leading to the change in the stress field, which will react on the temperature field. Therefore, the hot forming process is a change process with co-existence and mutual coupling of the internal temperature field and stress field, and this mutually coupled change process requires that the material components should be adaptable to the thermal cycle of hot forming process.

However, for 10CrNi3MoV marine steel, in the heating and quenching process, the surface is very likely to generate oxidation and de-carbonization due to sharp high temperature-cooling, which is accompanied by the change of other alloy element contents [8]. The nearer the location to the material surface is, the more obvious the de-carbonization and other chemical element change will be, forming a gradually changing microstructure (Fig. 1b), which comprises ferrite structure, ferrite-martensite mixed structure and complete martensite structure in sequence from surface to interior. In addition, the crystal structure becomes finer compared with that before hot forming and their size distribution is in a continuous and uniform state. It can be seen that the composition of

10CrNi3MoV marine steel is not fully adaptable to the thermal cycle of hot forming process.

Fig. 1c is the microstructure of the interior layer of hot-formed 10CrNi3MoV marine steel, which is of uniform lath martensite structure. This is because that, as the carbon content of the plate interior layer is low (0.07%-0.14%) and the martensite formation temperature is high (≥200℃), the microstructure of the interior layer of hot-formed 10CrNi3MoV marine steel is mainly of uniform lath martensite structure. The main cause of martensite strengthening is the solid solution strengthening due to oversaturated carbon. Besides, the structural refinement generated from martensite transformation also has the role of strengthening.

Results and Discussion

Hardness Change

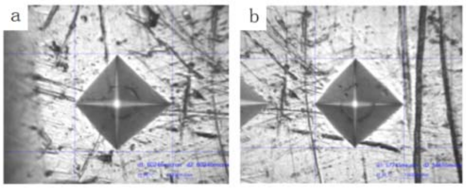

Fig. 2 Location for Hardness Testing

Fig. 2 shows the hardness tests at different depths from the surface. Fig. 2a shows the test at 0.05mm from the surface while Fig. 2b shows the test at 0.1mm from the surface.

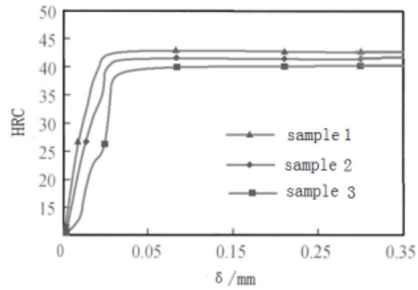

Fig. 3 Hardness Change along Thickness Direction of 10CrNi3MoV after Hot Forming

Fig. 3 is the hardness (HRC) change of distance δ along the thickness direction of hot-formed 10CrNi3MoV marine steel. It can be seen from Fig. 3 that the material hardness increases sharply from surface to interior within the 0-0.25mm surface depth scope, the change is basically in a linear increase and the hardness is maintained at 40-45HRC after reaching the 0.25mm depth. This indicates the impact of the surface gradually changing microstructure and the interior martensite structure of hot-formed material on hardness. That is, the surface is mainly of ferrite structure and has a low hardness, the middle layer is of ferrite-martensite mixed structure and has a hardness increasing with the increase of martensite content, and the interior layer is of complete martensite structure and has the highest hardness.

Malleability Change

Fig. 4 is the change of malleability ε of distance δ along the thickness direction of hot-formed 10CrNi3MoV marine steel. It can be seen from Fig. 4 that the material malleability decreases from surface to interior in sequence within the 0-0.25mm surface depth scope, with the change amplitude being great. The decrease amplitude is obviously reduced at the 0.25-0.50mm depth scope, and becomes very small after the 0.50mm depth is reached, indicating that the surface gradually changing microstructure and the interior martensite structure of hot-formed material also have impact on malleability, and the change law of malleability is basically consistent with that of hardness.

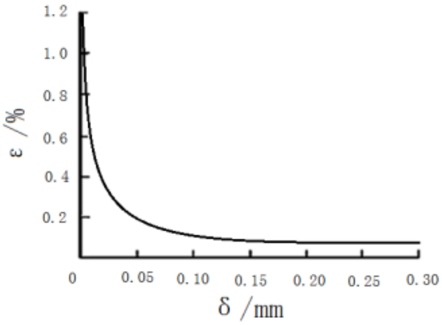

Fig. 4 Malleability Change along Thickness Direction of Hot-formed 10CrNi3MoV

Impact Resistance

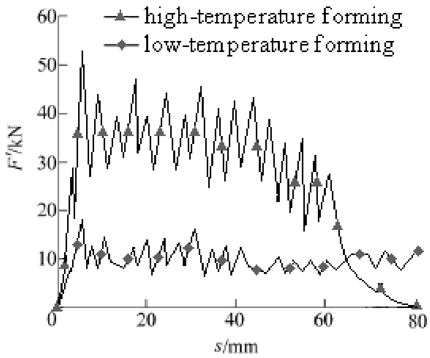

Fig. 5 Impact Force vs Displacement Curve of 10CrNi3MoV before and after Hot Forming

Fig. 5 is the impact force vs displacement curve under dynamic impact load of 10CrNi3MoV marine steel before and after hot forming. It can be seen from Fig. 5, before hot forming, 10CrNi3MoV marine steel has a great structural peak value, a poor malleability, a low impact resistance, an early loss of loading capacity and a poor impact resistance in the impact process. After hot forming, the role of its gradually changing surface microstructure and the display of large malleability characteristic by the soft outer layer prevent the interior high-strength martensite from premature failure in the impact process, and enable a gentle structural peak value. As a result, the gentle impact force level and the gradual failure of the material enable the structure to keep a high energy absorption and impact resistance.

The impact resistance test of hot-formed 10CrNi3MoV marine steel shows that when the impact velocity is great (> 1m/s), the effect of the impact process on the material deformation mainly depends on the yield strength of material. Even if it is an elastomeric impact, the energy consumption will cause unrecoverable plastic deformation. That is to say that, in the early and late periods of the impact process, not only the plastic deformation of the whole structural member but also that of the material at the impact point should be considered. In the early impact period, as the surface of hot-formed 10CrNi3MoV marine steel is of a gradually changing microstructure comprising ferrite structure, ferrite-martensite mixed structure and complete martensite structure, and the material surface is soft, when the impact occurs, and the impact velocity is greater than the initial plastic impact velocity, there will be "squeezing type" plastic deformation in the material surface. According to Hertz theory [13-14], the yield point of material is at 0.5a below the contact area center, and the relationship between the contact deformation and the contact area is:

$$a = (R\delta)^{1/2} \tag{1}$$

Where, a represents the radius of contact area, δ is the impact deformation amount and R is the equivalent radius of the impact object regarded as spherical. According to the low of conservation of energy [15]:

$$\frac{1}{2}mv^2 = \int_0^{\delta} P_e d\delta + \int_{\delta_y}^{\delta_{max}} P_{ep} d\delta \tag{2}$$

The maximum contact pressure generated in impact is:

$$P_{ep} = \pi R\left(\delta_{max} - \delta_y\right)\left(P_y - k\sqrt{\delta_y}\right) + \frac{4k\pi R}{3}\left[\delta_{max^{\frac{3}{2}}} - \frac{(\delta_{max} + \delta_y)^{\frac{3}{2}}}{2}\right] + P_y \tag{3}$$

Where, y is normal deformation direction; m is equivalent mass; v is impact velocity, δ_{max} is the maximum amount of impact compression; δy is the normal compression amount of the relative squeezed deformation central point of contact; k is strengthening coefficient, which is a definite parameter for a given material and related only the physical and mechanical properties of the material; Pe is the maximum contact pressure generated in sphere impact; Pep is the impact pressure of elasto-plastic impact; and py is the compressive yield stress of contact.

The plastic deformation process of material surface can effectively reduce the maximum contact pressure of surface and its acceleration peak value during the impact by collider. The easier the plastic deformation, the greater the value reduction will be. The gradually changing microstructure formed in the surface of hot-formed 10CrNi3MoV marine steel is characterized by high plasticity and easy deformation due to the existence of ferrite, which can not only reduce the maximum contact pressure of surface and its acceleration peak value but also reduce the maximum contact pressure and slow down the follow-up impact deformation process in the early period of impact by collider. In the middle period of impact, the surface plastic deformation continues and extends to the interior. However, the squeezing type plastic deformation rate at the impact point decreases and the absorbed energy is also reduced. But, the structural member starts the integral bending plastic deformation at this time, the dynamic energy of the collider begins to decrease rapidly, the vibration resilience of impact makes the acceleration rise once again and the plastic deformation of the material surface does not end yet. With the progress of impact, when the normal pressure exerted is greater than the initial yield normal pressure, the collider begins to unload according to the unloading control equation [16]:

$$\frac{1}{2}mv_r^{\,2} = \frac{2\pi^2}{10}\frac{(3\sigma)^2(R\delta_{max})^{\frac{3}{2}}}{E_{ul}} \tag{4}$$

Where, v_r represents resilience velocity, v_r is resilience modulus, and σ is the yield strength of material. With the increase of deformation, the yield point location extends to the interior of material, and the surface plastic deformation area also extends toward the interior of material. However, at the impact site, the squeezing type plastic deformation rate and also the absorbed energy are reduced. As the interior of hot-formed 10CrNi3MoV marine steel is of a microstructure comprising mainly martensite, the material hardness and strength are made to increase continuously. The integral yield deformation of the structural member can effectively absorb the impact energy, and at this time, the structural member reduces the impact energy by integral deformation. With the proceeding of the impact process, the impact of the squeezing type plastic deformation at the impact point on dynamic energy absorption becomes less and less, and the structural member now mainly relies on gentle yield deformation to absorb the remaining impact dynamic energy. In the late period of impact, after the absorption of a large amount of dynamic energy, the collider velocity will continue to decrease. According to the expression $\frac{1}{2}mv^2$ of dynamic energy, the collider velocity will quickly decrease with the reduction of dynamic velocity, and finally the collider will stop, ending the impact deformation process.

It follows that the gradually changing microstructure formed in hot-formed 10CrNi3MoV marine steel facilitates the reduction of the peak impact level of structure, and meanwhile, the gentle impact and the gradual failure of material enable the structure to keep a high energy absorption capacity. The gradually changing microstructure formed in 10CrNi3MoV marine steel after hot forming combines the excellent properties of single-phase materials, and is suitable for structural members that should withstand impact and absorb energy, being of positive significance to ship design requiring both excellent impact resistance and good energy absorption.

Conclusions

1) Before hot forming, 10CrNi3MoV marine steel has a tempered sorbite structure with martensitic direction characteristic. After hot forming, influenced by sharp hot-cold interaction, oxidation and de-carbonization, a gradually changing microstructure is formed in the surface, which comprises ferrite structure, ferrite-martensite mixed structure and complete martensite structure that are in sequence from surface to interior, and the interior structure of the steel mainly comprises uniform lath martensite.

2) The gradually changing microstructure formed in the surface of hot-formed 10CrNi3MoV marine steel makes the material hardness increase from surface to interior and the malleability decreases from surface to interior. Especially, the gradually changing microstructure in the surface and the display of large malleability characteristic by the soft outer layer prevent the interior high-strength martensite from premature failure in the impact process and facilitates the reduction of structural peak impact, and the gentle impact level and the gradual failure of the material enable the structure to keep a high energy absorption capacity and impact resistance.

Acknowledgement

Science and Technology Plan Leading Project of Fujian Province (2016H0023); Natural Science Foundation of Fujian Province (2014J01200); Science and technology project of Fujian provincial education ministry of China (No. JA13189)

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