EFFECT OF MICROSTRUCTURAL HOMOGENEITY ON MECHANICAL AND THERMAL FATIGUE BEHAVIOR OF A HOT-WORK TOOL STEEL

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Abstract 4Cr5MoSiV1(AISI H13) steel, a widely used for hot-work tool steel, composes Cr, Mo, V alloying elements that easily form carbides. The type and distribution of carbides deeply affect its mechanical properties and thermal fatigue behavior. The impact toughness and thermal fatigue behavior of 4Cr5MoSiV1 steel were investigated in this paper. Primary carbides and microsegregation which deteriorate impact toughness, exist in the electroslag remelting ingot. Adopting homogenizing and appropriate preheat treatment, primary carbides can almost dissolve, and eliminate microsegregation at the same time. So carbon and alloying elements distribute homogeneously, and the secondary carbides distribute on the ferrite matrix homogeneously, which can all increase impact toughness value. The paper also tested the thermal fatigue behavior using Uddeholm self-restrict thermal fatigue testing apparatus. The type of carbides changed during thermal fatigue test, the more thermal fatigue cycles experienced, the larger the diameter of carbides was, and those two factors decreased microhardness of the surface layer. The results indicated that 4Cr5MoSiV1 steel had good thermal fatigue resistance after homogenizing.

Keywords: H13 steel, impact, toughness, thermal fatigue, carbides

INTRODUCTION

4Cr5MoSiV1 (AISI H13 steel) steel, a widely used hot work tool steel with good thermal fatigue resistance, good impact toughness, tempering resistance, is used as die casting dies to produce industrial components of aluminium, magnesium and zinc alloying [1]. Microsegregation of chemical elements and eutectic carbides exists in 4Cr5MoSiV1 steel produced by traditional process, which will deteriorate the mechanical and thermal fatigue behavior [2, 3]. The testing results indicate that the impact toughness value of transversal direction is only 30-40 percent to that of longitudinal direction of a 4Cr5MoSiV1 steel block with large cross section. However, the ratio of impact toughness value (transversal impact toughness value/longitudinal impact toughness value) is over 0.8 of Uddeholm 8407s steel with a considerably homogenous microstructure. In order to increase the impact toughness value and improve the mechanical and thermal fatigue behavior of 4Cr5MoSiV1 steel, traditional process must be improved and adopt homogenizing annealing process. The primary carbides and microsegregation can be eliminated by means of homogenizing process. Uniform microstructure can be gained after homogenizing and then the mechanical properties of 4Cr5MoSiV1 steel, especially the impact toughness value, area reduction and elongation rate, increase sharply, in the end, the thermal fatigue resistance can be improved as well as prolong the life of the dies.

EXPERIMENTAL METHODS AND RESULTS

MATERIALS AND HEAT TREATMENT

The chemical compositions of testing materials were tabulated in Table 1. The chemical compositions of Uddeholm 8407s steel were also shown in Table 1. From the result in Table 1, both 4Cr5MoSiV1 steel and Uddeholm 8407s steel were with almost the same content of main chemical elements, but the content of trace elements of Uddeholm 8407s steel, such as sulphur and phosphorus, was much lower than that of 4Cr5MoSiV1 steel. Even though, the chemical compositions of the two steels used are both within the range of H13 steel of NADCA 207-90 standard. According to paper [4], the lower the content of sulphur in die casting dies, the better the thermal fatigue resistance will be. Steel ingot is refined by electroslag remelting (ESR) in order to decrease the content of sulphur, and then the ESR ingot soaks at a considerably high temperature for a long time, (i.e. homogenizing annealing), then it is forged at the temperature range of 1100 ℃ and 900 ℃. Large strains are obtained during forging the ingot, and spheroidizing annealing is conduced to obtain uniform microstructure without primary carbide and microsegregation.

Table 1. Chemical compositions of 4Cr5MoSiV1 and Uddeholm 8407s steel used (wt%)

Brand	C	Cr	Mo	V	Si	Mn	S	P
4Cr5MoSiV1	0.38	5.11	1.25	0.86	1.01	0.31	0.003	0.012
8407s	0.40	5.14	1.46	0.93	1.02	0.41	0.0005	0.009

The 4Cr5MoSiV1 steel produced by traditional process (i.e. 4Cr5MoSiV1 steel produced without homogenizing) is symbolized A, the 4Cr5MoSiV1 steel subjected to homogenizing is symbolized B. Both material A and material B were austenitized at 1010 ℃ for 30 minutes, then oil cooled to room temperature. Tempering was effected for 2h×2 at temperature of 610 ℃ and air cooled to room temperature. The heat treatment of all specimens was carried out in vacuum furnace in order to limit decarburization.

MECHANICAL PROPERTIES

The hardness of annealed state and quenched and tempered state of material A and material B is shown in Table 2 and Table 3. Hardness determination of annealed state was carried out by HB-3000 hardometer, and that of quenched and tempered state was determined by 69-1 hardometer. From the data in Table 2, we can conclude that the annealed hardness of two materials was almost the same, but it was a litter lower than that of the Uddeholm 8407s steel. And there was no difference in hardness after quenching and tempering, the hardness after quenching and tempering was 46 HRC.

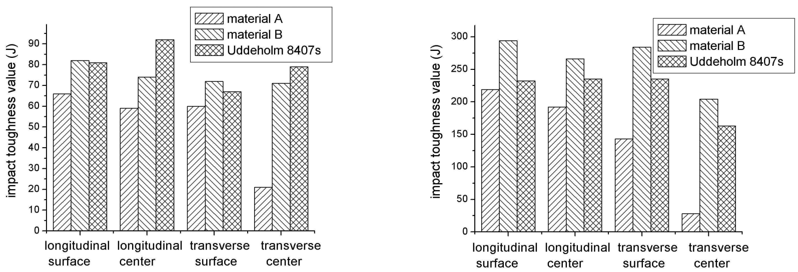
Table 2. Hardness of material A, B and Uddeholm 8407s steels in annealed state

	material A	material B	Uddeholm 8407s
HB	173	178	199

Table 3. Hardness of material A, B and Uddeholm 8407s steels after quenching and tempering. Austenitized at 1010 ℃ for 30min, tempered at 610 ℃ for 2h×2

	Material A	Material B	Uddeholm 8407s
HRC	46	46	47

Determination of tensile strength, σ_b , elongation, δ_{10}, area reduction, ψ, were carried out by MTS-80 testing machine at room temperature. Four locations in the steel block were selected to determine these mechanical properties, the specimens were selected from the surface and core of longitudinal direction and those of transversal direction. Table 4 and Table 5 show the results of material A and material B respectively, as a contrast, Table 6 show the corresponding data of Uddeholm 8407s steel. Fig. 1 shows the impact toughness value. The impact toughness value was determined by JB-30B impact testing machine with a maximum impact capacity of 300 J. The impact samples of annealed state were U-notched and the impact samples of quenched and tempered state were non-notched. Each sample was milled to 10.3 $\times$ 7.3 mm square by a length of 55 mm prior to heat treatment, then finished to 10 $\times$7 mm square (tolerance $\pm$ 0.05 mm). Five samples were prepared for each group of test, and the average test value calculated. As the data indicats, the mechanical properties of 4Cr5MoSiV1 steel increased sharply after homogenizing, especially the



(a) (b)

Figure 1. a) annealed impact toughness value and b) quenched and tempered impact toughness value of material A, material B and Uddeholm 8407s steel.

Table 4. Tensile strength, σ_b , elongation, δ_{10}, and area reduction, ψ, of annealed and quenched and tempered material A.

	Annealed material A				Quenched and tempered material A			
	longitudinal		transversal		longitudinal		transversal	
	surface	center	surface	center	surface	center	surface	center
σ_b [MPa]	592	602	595	590	1531	1550	1563	1520
δ_{10} [%]	24.1	24.8	25.1	23.1	9.1	8.4	7.1	5.5
ψ [%]	62.6	62.8	64.1	46.7	45.5	42.4	41.2	10.3

Table 5. Tensile strength,σ_b, elongation, δ_{10}, and area reduction, ψ, of annealed and quenched and tempered material B.

	Annealed material B				Quenched and tempered material B			
	longitudinal		transversal		longitudinal		transversal	
	surface	center	surface	center	surface	center	surface	center
σ_b [MPa]	617	616	609	606	1457	1465	1598	1606
δ_{10} [%]	26.3	25.1	24.7	24.5	8.7	7.7	6.7	6.3
ψ [%]	69.2	69.4	69.1	66.7	54.5	51.8	40.7	37.8

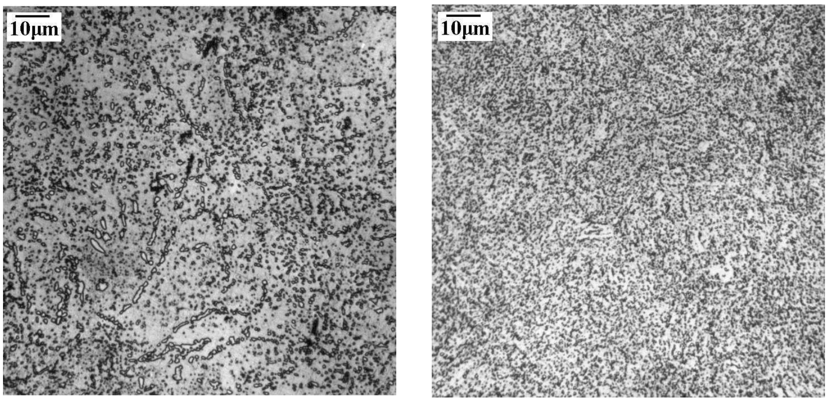
Table 6. Tensile strength, σ_b, elongation, δ_{10}, and area reduction, ψ, of annealed and quenched and tempered Uddeholm 8407s.

	Annealed Uddeholm 8407s				Quenched and tempered Uddeholm 8407s			
	longitudinal		transversal		longitudinal		transversal	
	surface	center	surface	center	surface	center	surface	center
σ_b [MPa]	670	668	683	664	1518	1557	1546	1520
δ_{10} [%]	24.2	24.6	23.0	23.1	9.6	8.7	8.7	7.6
ψ [%]	65.9	65.4	64.2	63.8	52.8	51.8	42.1	39.3

specimens of transversal direction in the central steel block. The ratio R (R equals to impact toughness value of transversal direction /impact toughness value of longitudinal direction) of material A was only about 0.3, however, the ratio R of material B increased to 0.8 after homogenizing which reached the level of Uddeholm 8407s steel. In another words, it mean that the impact toughness value of transversal direction in the steel block improved and the microstructure became uniform.

METALLOGRAPHY AND SEM EXAMINATION

The microstructure of each testing sample was observed by NEOPHOT 21 metallographic microscope. Fig. 2 shows the microstructure of material A and B. From the metallograph there exists eutectic carbides and grain boundary secondary carbides in the annealed material A, however, Fig. 2b showed uniform microstructure of material B. Secondary carbides are distributed homogeneously on the ferrite matrix without primary carbides and microsegregation.

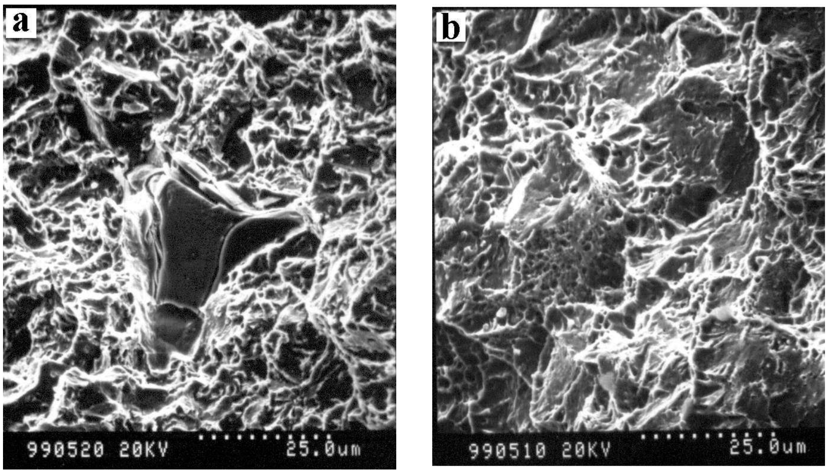


(a) (b)

Figure 2. Metallograph of annealed specimens, a) metallograph of material A; b) metallograph of material B.

Fig. 3 shows the fractographies determined by a scanning electron microscope (SEM) HITACHI S-570. Fig. 3a is the fractograph of material A. A small plate was observed in the center of the fractograph, it testified a primary carbide enriched with vanadium using energy dispersive spectroscopy, EDS. Transgranular quasi-cleavage and intergranular cleavage were both observed in the fractography. Fig. 3b was the fractography of material B, analysis on the fracture surface of material B indicated that considerable plastic deformation occurred during the fracture process. The predominant fracture mode displayed by these specimens was transgranular quasi-cleavage.

Electron-beam Probe Micro-analysis(EPMA) determination was made on both material A and B. It determined the Cr, Mo, V, and C elements every



(a) (b)

Figure 3. SEM fractographes of quenched and tempered specimens, a) material A; b) material B, austenitized at 1010 ℃ for 30 minutes and tempered at 610 ℃ for 2h×2.

0.03 mm using wave dispersive spectroscopy(WDS). The total number of determining spots were 30 to record the counter number. Then calculated the root-mean-square deviation was calculated, σ_s, in line with data which can indicate the segregation of the chemical elements examined. The result was tabulated in table 7. The root-mean-square deviation of Cr, Mo and V elements in material A was higher than that in material B, it indicated that these elements existed solidifying segregation phenomenon.

Table 7. The calculation results of root-mean-square deviation of Cr, Mo, V, and C elements in material A and B.

	Material A				Material B			
	Cr	Mo	V	C	Cr	Mo	V	C
σ_s	221	21	67	73	183	9	30	100

THERMAL FATIGUE TESTS

According to paper [5], thermal fatigue was defined as "Gradual cracking due to many temperature cycles, a microscale phenomenon often in a thin surface layer of the tool". In this test, the thermal fatigue samples were taken from the center of the ingot parallel to the rolling direction. The shape and size of the thermal fatigue samples were shown in Fig. 4. All thermal fatigue samples were ground and polished to get mirror finish so as to minimize the damage of grinding. Thermal fatigue tests were held in a high frequency induction furnace, which was contributed by INDUCTOHEAT CORPORATION of America and rebuilt in our laboratory, now possessing much function such as automatic controlling of heating, cooling and recording the cycle number. According to the thermal fatigue test standard of Uddeholm Company, the standard of self-restricting heat-cool fatigue test, the cycle was designed as follows:

Temperature range: room temperature (18℃) 700℃; heating time: 3.6 sec; holding at heat: 1 sec; cooling time: 8 sec; holding at cool: 1 sec; cooling medium: water;

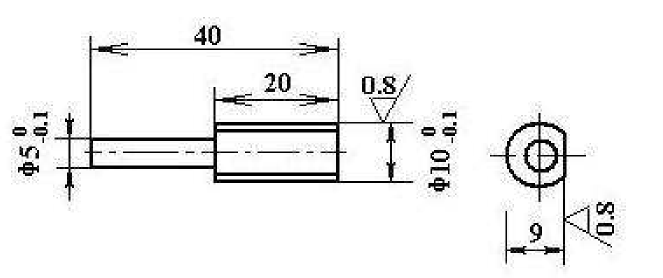


Figure 4. Shape and size of the thermal fatigue samples used in this tests.

Each sample was immersed into 10% hydrochloric acid to eliminate oxide layer, then observed its thermal fatigue cracks using Nikon Stereoscopic Zoom Microscope SMZ645 after subjecting to 3000 cycles. Fig. 5 showed the morphology of thermal fatigue cracks of material A and B. From Fig. 5a, which was the morphology of thermal fatigue cracks in material A, the longitudinal cracks developed rapidly, connected together and formed the main crack. It was obvious in these two figures that the damage level of thermal fatigue cracks in material A was severer than that in material B, since there were many longitudinal cracks penetrating all the area of the sample in the former but only relatively fine and equable net cracks in the latter.

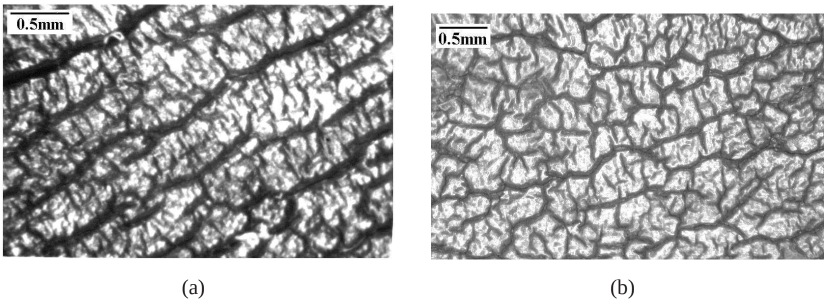


Figure 5. Morphology of the thermal fatigue cracks observed by stereoscopic microscope a) material A; b) material B.

DISCUSSION

The mechanical properties of material B was superior to that of material A, especially the transversal direction properties in the core of the steel block of material A, such as the impact toughness value, which was only 30% of that of longitudinal direction. This phenomenon was induced by several factors. First, there existed severe chemical elements segregation in the ESR ingot, Cr, Mo and V congregated at some certain area to form eutectic carbides such as VC. It formed stripe structure which enriched with C and alloy elements or impoverished of these elements and distributed alternatively after the ingot being forged, thus obtaining a considerable degree of anisotropy [6]. Second, eutectic carbides and grain boundary secondary carbides both deteriorated the impact toughness to a great extent. Eutectic carbides particles embedded on the equiaxed ferrite matrix, and grain boundary secondary carbides existed at some locations of material A as shown in Fig. 2a. However, material B (i.e. 4Cr5MoSiV1 steel block after homogenizing) had a quite uniform microstructure with fine spheroidized secondary carbides particles in the ferrite matrix. From the fractograph of material A as shown in Fig. 3a , the feature of the fracture surface was intergranular cleavage mainly, some small cleavage facets was observed on the fracture surface. Secondary carbides and tramp and trace elements precipitated at the austenite grain boundary, which caused microcracks to expand through grain boundary. As shown in Fig. 3b, there was a great proportion of dimples on the fracture surface of material B, it indicated that the impact sample subjected to great plastic deformation before its fracture. This type of fracture surface indicated that the material had relatively good ductility and toughness, which was supported by the average impact toughness value.

Strength, toughness, ductility and hardness of hot work-tool steel can all affect its thermal fatigue behavior. The thermal fatigue cracks usually expand through the grain and other places whish has relatively low strength and bad toughness. From the impact toughness value, we can see that it has a considerably low impact toughness value of transversal direction in the core of the steel block of material A. So the thermal fatigue cracks expand through transversal direction of the steel block and formed main thermal fatigue cracks eventually, the dies will fail to service early when these main cracks become wide and deep to a certain extent. There is the same impact toughness of longitudinal and transversal direction of material B, on the contrary, and the thermal fatigue cracks expand evenly during the thermal fatigue tests inducing to long service life of dies.

CONCLUSION

Stripe segregation and eutectic carbides in 4Cr5MoSiV1 steel decrease sharply impact toughness, especially the transversal impact toughness in the core of the steel block. Adopting homogenizing annealing process, we can eliminate segregation and eutectic carbides, and then improve mechanical properties of 4Cr5MoSiV1 steel. The impact toughness value of short-transversal direction in the core of the steel block can increase from 28 J to 204 J, reaching the level of Uddeholm 8407s steel. So one can obtain a high degree of isotropy of mechanical properties and microstructure.

The thermal fatigue behavior of 4Cr5MoSiV1 steel can also be improved through homogenizing. Subjecting to same heat-cool cycles, 4Cr5MoSiV1 steel shows good thermal fatigue resistance with small, net thermal fatigue cracks after homogenizing. However, it shows a relatively bad thermal fatigue resistance with bulky, parallel thermal fatigue cracks without homogenizing.

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