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EVALUATION OF THE MECHANICAL PROPERTIES OF NIOBIUM MODIFIED CAST AISI H 13 HOT WORK TOOL STEEL

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Abstract: *In this research, the effects of partially replacing of vanadium and molybdenum with niobium on the mechanical properties of AISIH 13 hot-work tool steel have been studied. Cast samples made of the modified new steel were homogenized and austenitized at different conditions, followed by tempering at the specified temperature ranges. Hardness, red hardness, three point bending test and Charpy impact test were carried out to evaluate the mechanical properties together with characterizing the microstructure of the modified steel using scanning electron microscope. The results show that niobium addition modifies the cast structure of Nb–alloyed steel, and increases its maximum hardness. It was found that bending strength; bending strain, impact strength, and red hardness of the modified cast steel are also higher than those of the cast H13 steel, and lower than those of the wrought H13 steel.*

Keywords: *Hot-work tool steel, H13, Nb, niobium, NbC, mechanical properties.*

1. INTRODUCTION

Nowadays, AISI H13 is one of the most famous hot-work tool steels and dies [1], which is widely used as die casting and hot forming dies [1]. High toughness, high hardenability, good machinability, low distortion during heat treatment and low cost have made this steel as a very useful tool steel [1]. The as cast structure of this steel, as mentioned in the previous paper [2], consists of some eutectic chromium carbides plus semi globular MC, vanadium carbides, and M_6C, molybdenum carbides, in a martensitic matrix. The steel with this microstructure doesn't have desirable mechanical properties, due to the presence of eutectic structure, and therefore, makes it necessary the microstructure to be modified by hot-working. It is reported that [3,4], spray forming is an effective way to manufacture the cast-H13 steels as near-net-shape molds, dies, and related tooling.

The microstructure of austenitized and quenched wrought H13 steel consists of martensite and retained austenite [5]. There can be some MC carbides at austenite grain boundaries, if the cooling rate is insufficient [5]. Hardness of the quenched steel increases with increasing heating temperature, due to increasing the amount (about 1 vol.% [5,6]) of dissolved carbides in the matrix. Although, high temperature austenitization raises the retained austenite, it is not enough to decrease the hardness of steel [5]. Increasing heating temperature can also increase the hardenability, decreasing the bainite formation, increasing the homogeneity of steel, and leads to austenite grain growth [6]. Formation of bainite, with coarser structure than martensite, decreases the toughness of the steel [7].

The H13 steel has a mild secondary hardness, induced by tempering, during which large amounts of ultra fine carbides form on martensite plains, twin boundaries, and dislocation [8]. Tempering the steel at temperatures higher than this secondary hardening peak makes it soft, due to over tempering phenomenon [9].

Niobium is a strong carbide former element, producing MC carbide [10]. This carbide forming from the beginning of solidification can refine the cast structure [2]. On the other hand, because of having low solubility in austenite [11], this carbide, isn't dissolved in it, even at high temperature [12], hence it can control the austenite grain growth [10,11]. Science the as cast H13 steel does not have desirable mechanical properties, some researches have been done to change the standard composition of H13 in the new one [13], associated with adding the rare earth metal for modification the cast microstructure [14]. As one of the authors (Sh.Kheirandish) has some experiences on the substitution of standard alloying elements of the high speed steel [15], and the hot-work tool steel [2] with Nb, the aim of this research is to substitute the primary carbides of H13 steel, which are explained earlier to be Mo_6C and VC carbides, by NbC to produce the cast hotwork tool steel, in which 0.5% V and 0.4% Mo were replaced by 1.1 % Nb [2].

2. EXPERIMENTAL PROCEDURES

The melt was prepared in a 25 kg induction furnace with the max. frequency of 3 KH, max. power of 75 KW, and 1200 V without protecting gas, and poured at 1600°C in the ceramic investment mould at room temperature to make cubic (14×14×14 mm) and rectangular (10.5×10.5×55 mm) samples. The cast samples were homogenized at 950, 1000, and 1050°C for 1 to 3 h using electrical furnace with ±3°C accuracy. Homogenized samples were austenitized at the conditions shown in table 1 using the same furnace, followed by oil quenching and double tempering for 1 h at 350, 450, 550 and 650°C.

Metallography examinations were done by light microscope and SEM electron microscope attached with EDS analyzer. Hardness of samples was measured by Rockwell C machine with the accuracy of 1 HRC. Standard Charpy test was also done to measure the impact toughness of samples. Mechanical strength of the new steel was studied by three points bend test on 7×10×26 mm specimens with 0.3 mm/s strain rate. Fractured surfaces of the bending samples were also studied by SEM for better understanding of the fracture behavior of the specimens. To evaluate the ability of the modified steel to keep its hardness after holding at high temperature for 4 hours, the retained hardness of samples at room temperature (red hardness) was measured [16].

Each result of mechanical properties is the mean of at least 5 measurements of hardness, 4 measurements of Charpy test, and 3 measurements of bending test.

3. RESULTS AND DISCUSSIONS:

The compositions of the standard wrought and cast H13, and also the cast Nb-modified H13 are given in table 1. Fig. 1 shows the general view of as-cast microstructure of the modified steel. Niobium carbides, point A, in martensitic matrix can be seen in this figure. There are some light areas, point B in this fig., which are due to the Cr segregation during solidification. A brief discussion of the cast microstructure of this steel was given in the previous paper [2].

Figs.2 a and b show the microstructure of homogenized and austenitized samples after heating at 950 and 1100°C respectively, followed by oil quenching. The shape and amounts of niobium carbides, point A, don't change upon

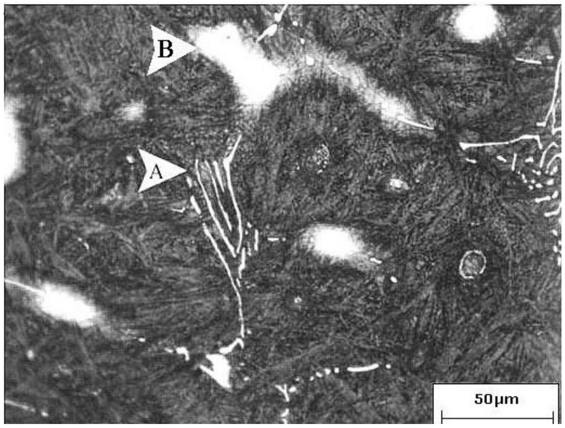

Fig. 1. Cast microstructure of the Nb-modified H13 steel, showing NbC network, point A, high concentration of chromium area, point B, in martensitic matrix.

Table 1. Composition (wt %) of wrought and cast H13, designed steel and modified H13.

	C	Mn	Si	Cr	Ni	Mo	V	Nb
Wrought H13	0.4	0.35	1	5.2	0.2	1.35	1	---
Cast H13	0.44	0.4	1.1	5.3	0.08	1.58	1.1	---
Nb modified H13	0.47	0.4	1.1	5.2	0.1	1.05	0.6	1.0

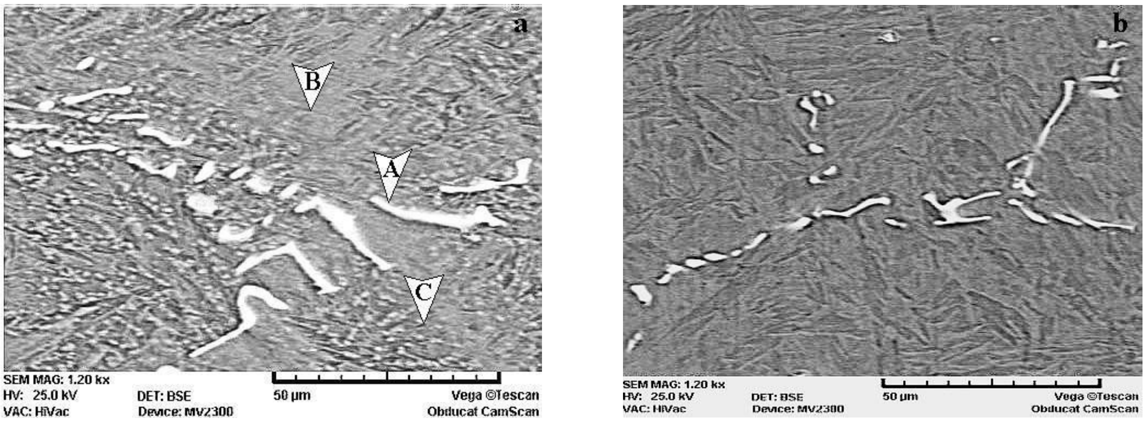

Fig. 2. SEM microstructures of homogenized and austenitized modified H13 steels at a- 950oC, and b- 1100oC.

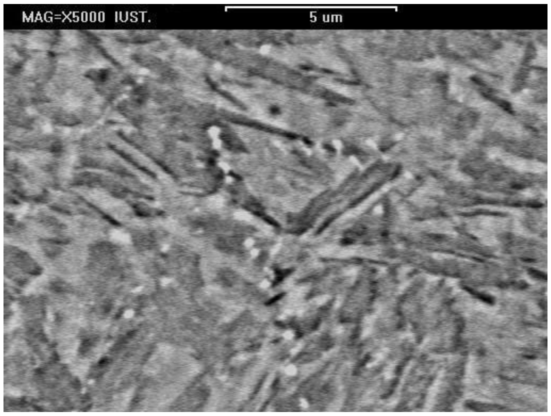

Fig. 3. Lath martensite matrix of the quenched modified H13 steel.

austenitizing due to their high stability [11] and low solubility in austenite [12]. The matrix point B, are lath martensite formed during oil quenching, which can clearly be seen at higher magnification, fig.3. There are also some fine vanadium and molybdenum carbides, point C, fig.2a, which are not dissolved in austenite as a result of applying insufficient austenitization temperature. As shown in fig.2b, these fine carbide particles are dissolved in matrix when applying the higher austenitizing temperature of 1100°C.

Fig.4 shows the hardness of the new steel, cast and wrought H13 in as-quenched condition versus austenitizing time at different temperatures. As shown, hardness increased with increasing heating time and temperature, as a result of dissolution of more carbides in the matrix when applying higher temperature or longer time. This, in turn, results in the dissolution of more C, Cr, Mo and V in matrix,

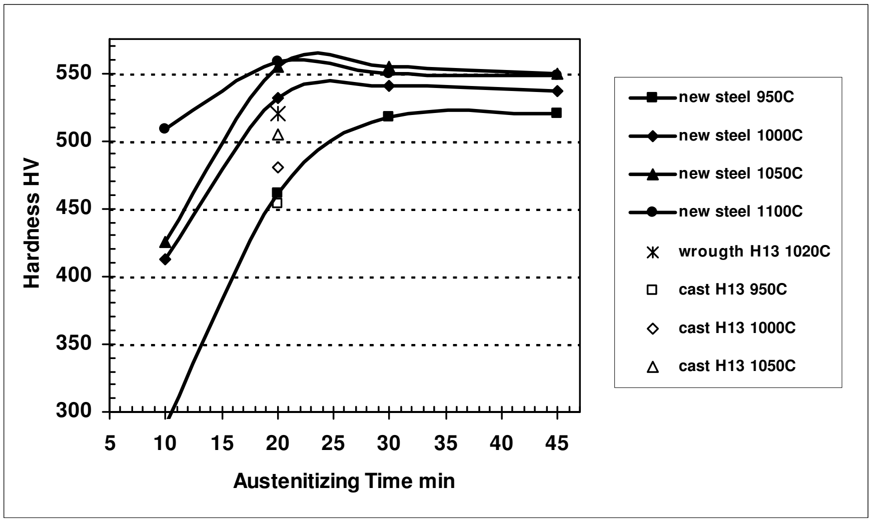

Fig. 4. As-quenched hardness of steels at different austenitizing times and temperatures.

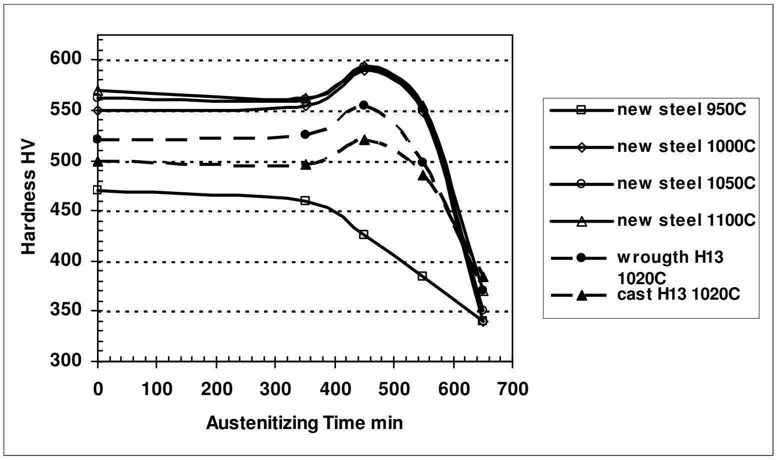

Fig.5. Hardness of steels versus tempering temperatures.

and therefore, the harder martensite will be formed after quenching. Fig.4 also shows that hardness decreases for austenitizing times of more than 20 minutes, resulting from the increasing of retained austenite in microstructure. In fact, increasing of the alloying elements dissolved in matrix decreases the MS temperature [5], and increases the amount of retained austenite. Although it is reported that [17] cryogenic treatment can completely remove the retained austenite, in the current research this phase is removed by tempering. It can be seen that hardness of the modified steel is always higher than that of the cast H13, which is due to the modification effect of Nb and better homogeneity of the microstructure of this steel compared to the cast H13 steel. The hardness of wrought H13 is also given in fig.4 for comparison purposes.

Variation of hardness with tempering temperature is shown in fig.5 for different austenitizing temperatures. As seen, the maximum hardness is obtained at the tempering temperature of 450^{o}C at all austenitizing temperatures, except 950^{o}C, which is attributed to the formation of the largest amounts of coherent secondary carbides of Mo and V [18]. Tempering at the higher temperature leads to rapid reduction of the hardness, resulting from over tempering phenomena, induced by losing the coherency of ultrafine carbides, and their further growth [19]. It seems that austenitizing at 950^{o}C can't produce an austenite with sufficient carbon and alloying elements; hence the secondary hardening doesn't occur during tempering at this condition [6]. The master hardness curve of the Nb-modified H13

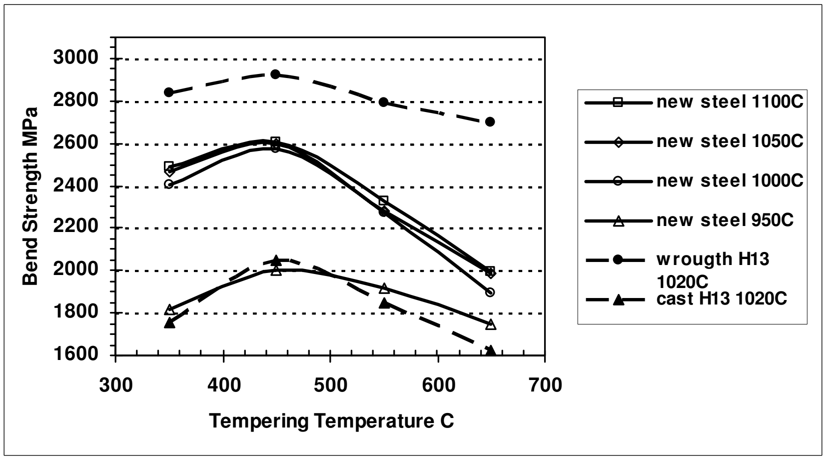

Fig. 6. Bending strength of steels versus tempering temperatures.

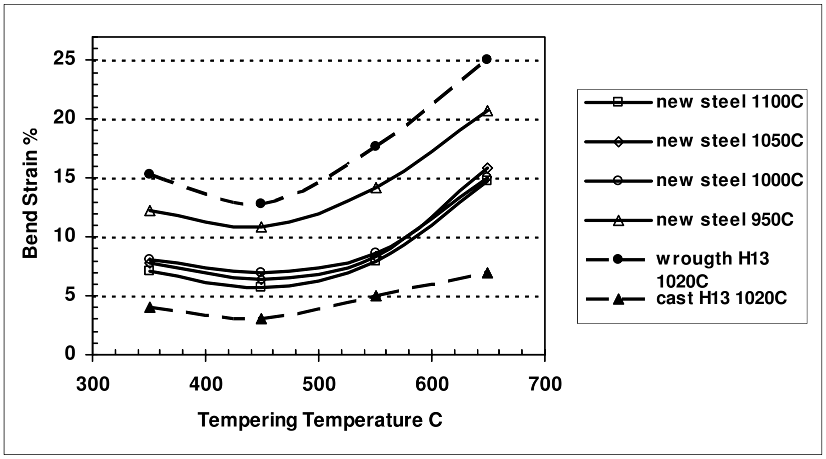

Fig. 7. Bending strain of steels versus tempering temperatures.

steel is higher than those of the cast H13, due to the more homogeneity of the microstructure of modified H13 steel. It can also be seen that this hardness is even higher than that of the wrought H13, due to the dominant effect of Nb in secondary hardening [20].

Figures 6, 7, and 8 show the variations of bending strength, bending strain and impact strength of samples, austenitized at different temperature, in terms of tempering temperature. It can be seen that the bending strength (fig.6) of all samples has a maximum strength at 450°C, at which the secondary carbides are precipitated from the matrix, acting as the barrier against dislocation movement [19]. The trend of variation can be explained the same as what mentioned for fig.5, but it must be noted that the wrought H13 steel always exhibits higher strength than the modified steel, while the inverse is true for the cast H13. This is due to the microstructure of these three steels. It means that, although the homogeneity of themodified steel is better than that of the cast H13, it is still lower than that of the wrought H13. Fig.6 also shows that applying the higher austenitizing temperature, results in the dissolution of more C and alloying elements in austenite, and therefore, formation of martensite with higher strength [21].

The same discussion can be used to explain the trend of variations shown for bending strain, fig.7, and fig.8.

As toughness of the steel decreases with increasing of its strength, the lower bending strain and impact strain are achieved at this condition. This is the reason for appearance of minimum points in all curves at the tempering temperature of 450°C,

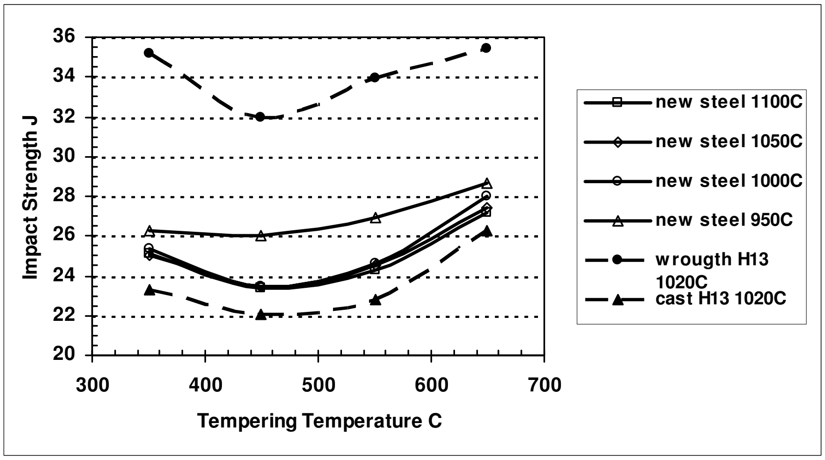

Fig. 8. Impact strength of steels versus tempering temperatures.

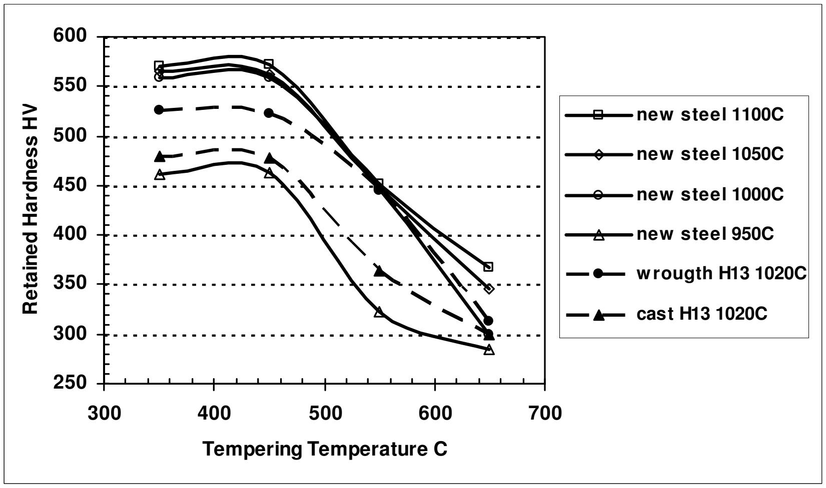

Fig. 9. Retained hardness (red hardness) of steels versus tempering temperatures.

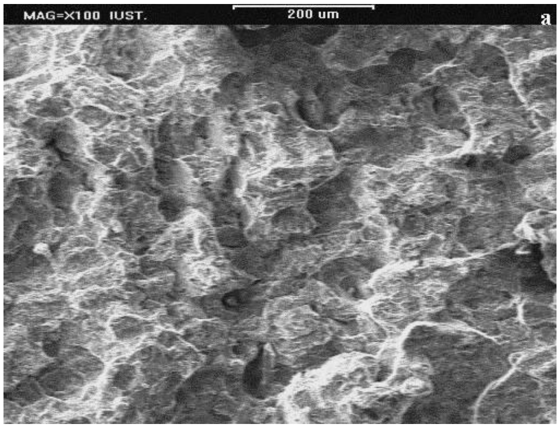

fig.10 a

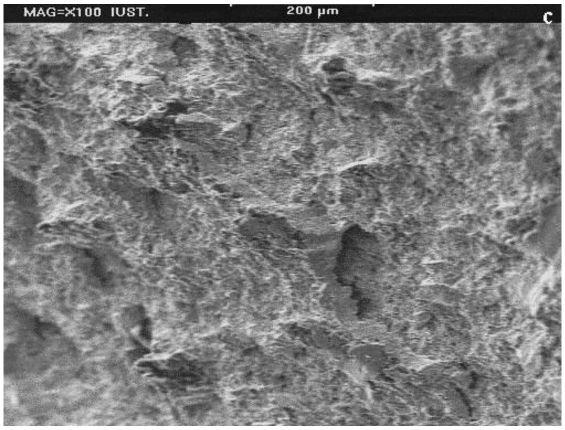

fig.10 c

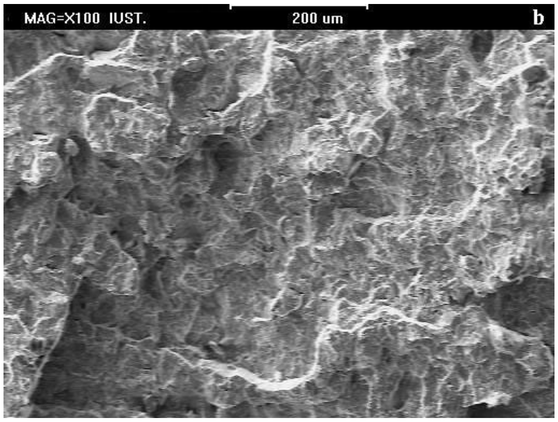

fig.10 b

Fig.10. Fracture surfaces of bending specimens of, **a**- cast H13, **b**- modified cast H13, and **c**- wrought H13 steels, austenitized at 1020 °C, oil quenched and double tempered at 450°C.a

figs. 7 and 8, where the maximum strength and hardness are achieved, figs 5 and 6. It can also be seen in these figs. That, the cast H13 has the minimum bending strain and impact strength, resulting from its heterogeneous microstructure, while the wrought H13 exhibits the maximum bending strain and impact strength, due to its homogeneous microstructure.

Variations of retained hardness, or red hardness, of all steels with tempering temperature are given in fig.9. As seen, hardness of all steels decreases after tempering temperature of 450°C, as a result of removing the coherencies of fine secondary carbides, and also growing the carbide particles [18]. It can be seen, from fig. 9, that retained hardness of modified steel, austenitized at 1000 to 1100°C can be even higher than that of the wrought H13, due to the effect of Nb on the resistance to softening [21].

Figs.10a, b and c show the fracture surfaces of bending specimens of the cast H13, the modified H13 and the wrought H13 steels respectively, austenitized at 1020 °C, oil quenched and tempered at 450 °C. The wrought H13, which has more homogeneous microstructure with distribution of semi globular fine carbides, has the finer and more homogeneous fracture surface, fig.10c, in comparison with microstructures of the unmodified and the modified cast H13. The more homogeneous fracture surface of the Nb-modified steel, fig.10b shows the finer and more homogeneous structure than the fracture surface of the cast H13, fig.10a. Hence, the modified H13 is more brittle than the wrought H13 steel, and more ductile than the cast H13.

CONCLUSIONS

Replacement of 0.5 wt% V and 0.4 wt% Mo by 1.1 wt% Nb in the cast AISIH 13 hot-work tool steel has the following results:

1. Microstructure of the modified steel is more homogeneous and finer than that of the cast H13 steel.
2. The modified steel has a secondary hardness about 600HV, at 450°C tempering temperature.
3. Hardness and red hardness of the modified steel is higher than those of the cast and wrought H13 steel.
4. Bending strength, bending strain and impact strength of the modified steel are higher than those of cast H13, but are lower than those of the wrought H13 steel.
5. The new modified cast tool steel heat treated at optimum conditions, homogenized at 1100°C for 1h, austenitized at 1000°C for 20 min, followed by oil quenching, and double tempered at 450°C for 1h has following mechanical properties: Hardness 590 HV, bend strength 2571 MPa, bend strain 6.9 %, impact strength 23.5 J.

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