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EFFECT OF CASTING AND HEAT TREATMENT ON CHANGE IN MICROSTRUCTURE AND MECHANICAL PROPERTIES IN AUSTENITIC HADFIELD STEEL

UTICAJ LIVENJA I TERMIČKE OBRADE NA PROMENU MIKROSTRUKTURE I MEHANIČKIH OSOBINA AUSTENITNOG HADFILDOVOG ČELIKA

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Abstract

Cast Hadfield steel is a material with high resistance to abrasion, provided, however, that it is used under the conditions of high dynamic loads. Typically, Hadfield steel starts with a harness value of 200HB after solution heat treatment and can reach values of over 600HB after work hardening. The above characteristics make it an ideal material for manufacturing casting components used in mining, crashing, drilling, steelmaking, naval, automotive and excavation applications. Manganese steel castings require a rapid water quench following the high temperature soak. A slack quench can reduce the toughness of the mterial dramatically. The mechanical properties of manganese steels are greatly enhanced by a fine grain size. Strength and ductility can be as much as 30% greater for fine-grained material. The refinement of the austenitic grain structure in Hadfield's Manganese Steel improves the weldability of the material, especially in cases where repair welding is required, in addition to enhancing the mechanical characteristics of the final products. This paper deals with the effect of heat treatment on casting process on the final properties of the Hadfield steel.

Rezime

Liveni Hadfild-ovi čelik je materijal sa visokom otpornošću na abraziju, međutim samo kad se koristi u uslovima visokih dinamičkih opterećenja. Tipično, Hadfild čelik počinje sa vrednošću tvrdoće od 200HB nakon termičke obrade rastvorno kaljenje i može dostići vrednosti preko 600HB nakon očvršćavanja. Gore navedene karakteristike čine ga idealnim materijalom za proizvodnju livenih komponenti koje se koriste u rudarstvu, drobljenju, bušenju, proizvodnji čelika, pomorstvu, automobilskoj industriji i iskopavanju. Odlivci od manganskog čelika zahtevaju brzo kaljenje u vodi nakon zagrevanje na visokoj temperaturi. Usporeno kaljenje može dramatično smanjiti žilavost materijala. Mehanička svojstva manganskih čelika su značajno poboljšana finom veličinom zrna. Čvrstoća i duktilnost mogu biti i do 30% veće kod finozrnog materijala. Usitnjavanje austenitnog zrna u mikrostrukturi Hadfieldovog manganskog čelika osim mehaničkih karakteristika finalnih proizvoda, poboljšava i zavarljivost tog materijala u slučajevima potrebe reparaturnog zavarivanja. Ovaj rad se bavi uticajem termičke obrade i procesa livenja na konačna svojstva Hadfild čelika.

1. Introduction

Austenitic manganese steel was invented in 1882 by Sir Robert Hadfield from whom it took its commercial name (Hadfield Steel). It is a ferrous alloy, usually, containing 1.0-1.4 wt% carbon and 10-14 wt% manganese[1]. Similarly to nickel, sufficient additions of manganese can extend the γ-loop in the iron carbon equilibrium diagram and the austenitic structure can be sustained at room temperatures [2]. Hadfield steel alloys are known for their high toughness, high ductility and exceptional work hardening ability and wear resistance.

In the as-cast condition (fig.1) [3], the steel contains carbides and embrittling transformation product [4]. Carbides form in castings that are cooled slowly in the moulds regardless of mould cooling rates. These carbides can also form when the as-cast contains more than 1.0 %C or the addition of alloying element such as Cr, V, Ti, etc. They form in heavy section castings during heat treatment if quenching is ineffective in producing rapid cooling throughout the entire section thickness [4]. Casting structure of these steels is including of carbides as (Fe,Mn)3C that through appropriate heat treatment, it could be achieve full austenitic structure from these steels [5-7].

a) b)

Figure 1: *As Cast vs full austenitic Hadfield steel, a) As Cast Hadfield steel austenitic matrix with carbide precipitates, b) Cast Hadfield steel after solution treatment in water austenitic matrix free from the carbide precipitates*

Slika 1: *Liveni u odnosu na potpuno austenitni Hadfildov čelik, a) Liveni Hadfildov čelik, austenitna matrica sa karbidnim precipitatima, b) Liveni Hadfildov čelik nakon tretmana u vodi, austenitna matrica bez karbidnih taloga*

Solution heat treatment (fig.2) [8] of Hadfield steel increases the strength of the material by dissolving the soft carbide phases that precipitate on the grain boundaries during solidification but also results in the coarsening of the microstructure [9].

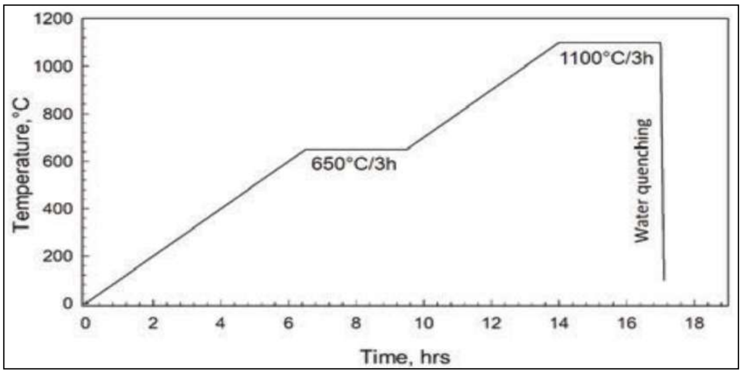


Figure 2: *Example of heat treatment process of the Hadfield steel*

Slika 2: *Primer procesa termičke obrade Hadfildovog čelika*

Microstructural refinement through inoculation (fig.3) with foreign particles or elements is a trending method, especially for light metal alloys and cast iron. Inoculants are added to the molten metal to promote the formation of fine and randomly oriented equiaxed grains during solidification.

a) b)

Figure 3: *Influence of pouring temperature on the grain refinement: a) Low pouring temperature, b) High pouring temperature*

Slika 3: *Uticaj temperature livenja na usitnjavanje zrna: a) niska temperatura livenja, b) visoka temperatura livenja*

The fluidity of manganese steel is quite high, approaching that of cast iron, which makes it is possible to fill intricate shapes and pour at low superheats. Most reliable method to obtain a fine grain structure is to pour the metal with low superheat just above its liquidus point [11].

Fig.3 [12] show the fracture surfaces of bars that were broken as cast to reveal the grain size. Both bars are from the same (12% Mn) heat with a) being poured at 1377°C and b) being at 1486°C.

In practice, pouring temperatures below 1427°C are typical for the 12% Mn grades and can be much lower as carbon and alloy levels are increased. Temperatures near 1371°C are desirable for pouring the higher manganese and carbon grades.

Currently, the industrial demand is to develop improved austenitic steel alloys for manufacturing components with longer operational life and reduced failure rates. In that way, the non-operational time of larger machinery during maintenance and part replacement would also be reduced and thus decrease operational costs, increase workforce productivity and improve sustainability.

Considering that operational life and failure rates of a casting component are directly connected with the material's mechanical properties which in turn are influenced by the microstructural features of the material such as the grain size, it is of high importance to investigate the reasons that cause them in relation to the casting process and heat treatment.

2. Case study no.1 castings with same chemical composition different grain refinement

The subject of comparison in this study are two castings, specifically excavation teeth (fig.4) for rotor excavator SRS 2000. Both are made of same chemical composition GX120MnCr13-2 (tab.1), but have different microstructure, more precisely different grain refinement.


a) b)

Figure 4: *Excavation teeth used for analysis of the effect of microstructure on mechanical properties:a) microstructure with dominant columnar grains, b) microstructure with dominant equiaxed grains*

Slika 4: *Zupci za iskop korišćeni za analizu uticaja mikrostrukture na mehanička svojstva: a) mikrostruktura sa dominantnim stubastim zrnima, b) mikrostruktura sa dominantnim jednakoosnim zrnima*

Table 1: *Chemical composition of cast steel GX120MnCr13-2 according to EN 10349*

Tabela 1: *Hemijski sastav livenog čelika GX120MnCr13-2 prema EN 10349*

Cast steel (Hadfield)	chemical composition in wt, %							
	C	Si	Mn	Cr	Fe	Cu	S	P
						Not more than		
						/	0.045	0.060
GX120MnCr13-2	1.05-1.35	0.3-0.9	11-14	1.5-2.5	rest	-	-	-


a) b)

Figure 5: *Microstructure - grain boundaries of both specimens: a) no presence of carbides along grain boundaries b) no presence of carbides along grain boundaries*

Slika 5: *Mikrostruktura - granice zrna oba uzorka: a) nema prisustva karbida duž granica zrna b) nema prisustva karbida duž granica zrna*

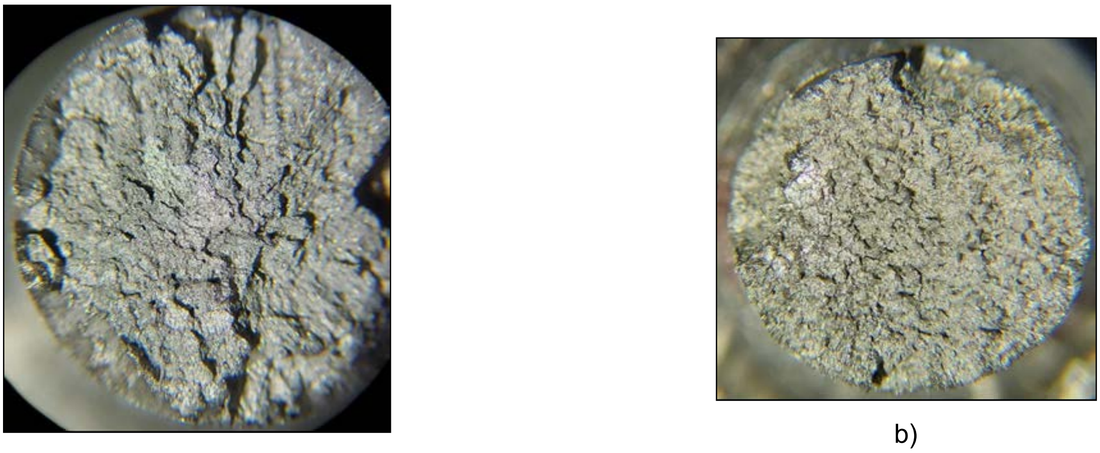
Fig.4 and fig.5 show that both samples of excavation teeth, produced by two different manufacturers, differ from each other in the applied grain size control mechanism.

Thus, the influence of this microstructural feature on the mechanical properties of the final product can be clearly differentiated. For this purpose, tensile and Charpy V-notch tests were performed on both samples. The comparison results are given in tab.2.

Table 2: *Results from tensile and Charpy V-notch test*

Tabela 2: *Rezultati testa zatezanja i Šarpijevog testa sa V-zarezom*

<table>
<tr><th>Speciment</th><th>$R_{p0.2}$ [MPa]</th><th>R_m [MPa]</th><th>A [%]</th><th>KV [J]</th></tr>
<tr><td>a)</td><td>446</td><td>742</td><td>31.5</td><td>36.0</td></tr>
<tr><td>b)</td><td>501</td><td>907</td><td>34.0</td><td>42.0</td></tr>
<tr><td colspan="5">Expected values for tensile test for Hadfield steel:</td></tr>
<tr><td colspan="3">coarse microstructure and section of 50mm
$R_{p0.2}$=445MPa,
R_m=634MPa,
A=37%,
Z=36%.</td><td colspan="2">refined microstructure and section of 50mm
$R_{p0.2}$=445MPa,
R_m=820MPa
A=45.5%
Z=37.4%.</td></tr>
<tr><td colspan="5">Expected values for Charpy V-notch test for Hadfield steel (DIN):
KV=16J at 22°C</td></tr>
</table>



a)

b)

Figure 6: *Macrostructure of the break surface of two speciments: a) coarse fracture surface, b) refined fracture surface*

Slika 6: *Makrostruktura površine preloma dva uzorka: a) površina grubog preloma, b) površina rafinisanog preloma*

This case shows that chemical composition is not a sufficient criterion (given in EN 10349-2012 *Steel castings -Austenitic manganese steel castings*) to evaluate the quality of the casting as a whole.

In summary, for Hadfield steel, grain refinement generally decreases hardenability due to an increase in grain boundary area, which impedes martensite transformation and reduces the maximum depth of hardening achievable—all while improving other mechanical properties such as strength and toughness.

Therefore, the microstructure should be a balance between the desired hardness obtained by impact hardening, as well as resistance to fracture under strong dynamic impacts.

A balanced microstructure will contribute to a longer lifespan of parts, as in the case of roto excavator teeth, in terms of wear, but also in terms of dynamic fracture.

3. Case study no.2 premature fracture failure of bucket tooth

The most common reasons for fracture failure of Hadfield steel excavator teeth are related to a combination of material defects, operational stresses, and environmental factors, with both metallurgical and external conditions playing important roles.

Metallurgical and materials defects-Fracture origins often include casting defects such as hot foundry cracks, large non-metallic inclusions, and porosities, which act as crack initiation sites during operation. Hadfield steel's tendency for carbide precipitation during post-cooling and improper heat treatment can cause brittle zones, micro-cracks, and a reduction in toughness.

Operational and enviromental factors-High impact and abrasive wear during excavation in tough mineral environments are key contributors, progressively weakening the teeth and causing cracks and fractures. Improper use, such as prying or using the teeth for unintended mechanical tasks, can overload or shock the steel, leading to premature failure. Exposure to chemicals that increase vulnerability to structure failure.

Other causes-Design flaws, such as unsuitable tooth geometry or uneven load distribution, further concentrate stress and encourage fracture under operational loads.

In case study no.2, a failure analysis is performed on a sample of series of broken excavator bucket teeth for rotor excavator [fig.7]. The exact chemical composition of the castings is GX120Mn12 according to EN 10349-2012.

Figure 7: *Example fracture surface of broken bucket tooth*

Slika 7: *Primer površine preloma polomljenog zuba kašike*

During operation, the microstructure of Hadfield steel changes because of work hardening. The mechanisms by which hardening occurs include twinning, stacking fault formation and dynamic strain. Fig. 8 shows for a work-hardened microstructure of manganese steel; clearly visible slip lines are the result of the work hardening to the grains.

Figure 8: *Work hardened manganese steel microstructure of the broken tooth*

Slika 8: *Mikrostruktura ojačanog manganskog čelika polomljenog zuba*

Due to the effect of work hardening, to isolate the effect of the load, an analysis was performed on an non hardened sample from the same manufacturing series. By abstracting the load, only the influence of possible metallurgical and material defects was analyzed. The fracture surface (fig.7) is also taken into account in the analysis of the broken tooth.

By analyzing the broken surface of the tooth (fig.7), it is possible to determine damage that originates from the presence of segregation and impurities. These defects in the material occurred during the casting of the tooth.

The most common defects that occur in this steel, in addition to segregations, are macro and micro pores. In fig. 8, macro pores (gray-blue fields) or cavities in the fracture surface are visible.

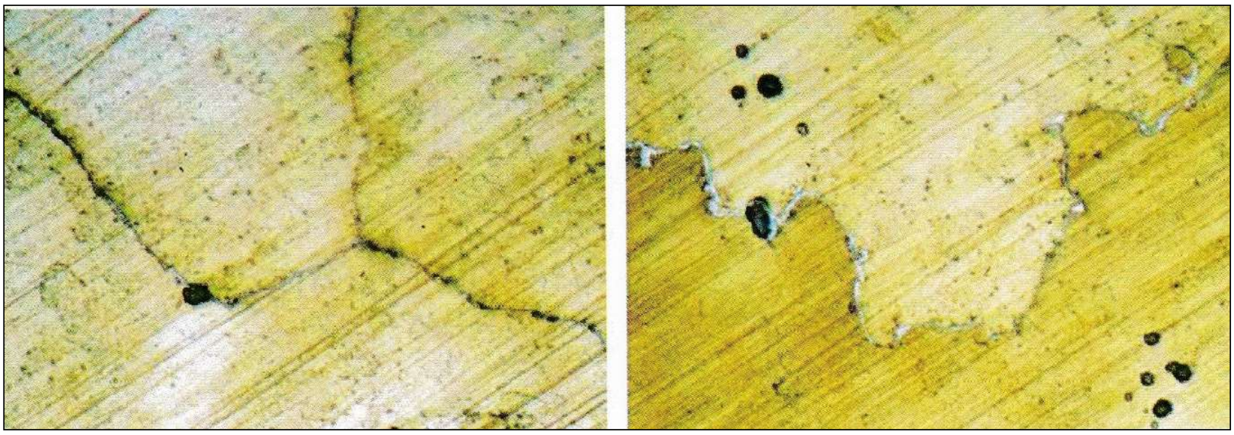


Figure 9: *Metallographic image of austenite grain boundaries-presence of undissolved carbides*

Slika 9: *Metalografski prikaz granica zrna austenita - prisustvo nerastvorenih karbida*

Metallographic samples were prepared from non hardened teeth from the same series as the the broken tooth (fig.7). The austenite grain boundaries are revealed with a 5% nital etchant for 15 seconds.

Table 3: *Chemical composition of cast steel GX120Mn12 according to EN 10349*

Tabela 3: *Hemijski sastav livenog čelika GX120Mn12 prema EN 10349*

Cast steel (Hadfield)	*chemical composition in* wt, %							
	C	Si	Mn	Cr max.	Fe	Cu	S	P
						Not more than		
						/	0.04	0.10
GX120Mn12	1.10-1.30	0.3-0.5	12-13	1.50	rest	-	-	-

By analyzing the obtained microstructure, it can be concluded that it is austenitic, with the presence of carbides along the grain boundaries (fig.9). The presence of carbides is observed whenever the carbon content is above 1% (tab. 3). In the presence of Cr, the separation of carbides is more intense. Two types of carbides are observed in the microstructure: in the form of nodules and elongated. The elongated ones are dominant.

As can be seen from this case, there are two types of metallurgical defects occurring in two different processes: during casting of the part and during solution heat treatment. Both processes, metallurgical by origin, failed to produce suitable microstructure so as to prevent structural defects (voids, cracks, inclusions) and the formation of brittle phases (carbides). This led to the tooth premature fracture failure and better weldability.

4. Conclusions

Manganese steel is used extensively in the mining industry and in other applications that require extreme toughness. The mechanisms for improving its properties are generally known. However, regardless of the improvements made to achieve better properties, if the part fails early in service, the gain is unlikely to be useful.

Therefore, it is necessary to pay attention to the following points before putting the castings into operation, in order to guarantee a long service life:

1. Checking the chemical composition is not a sufficient criterion to ensure that the castings have the required mechanical properties; in principle, it is one of several criteria that should be controlled during production (case no.1),
2. Microstructure control is a second mandatory criterion that the casting must satisfy in terms of grain shape and size, as well as the presence of other phases (case no.1),
3. The microstructure is the final record of the parameters of the casting process (presence of inoculants, pouring temperature, etc.); if they are not properly selected and implemented, the casting has weaker mechanical properties even though the chemical composition is met as a condition (case no.1 and 2),
4. The as-cast microstructure of Hadfield steel with an chromium content is composed of an austenitic matrix and alloyed cementite present mainly in the form of lamella,
5. The solution annealing increased the ductility of the as-cast alloys by the dissolution of the brittle carbides in the austenite matrix,
6. If the heat treatment is not optimized in terms of dissolution temperature, dissolution time, and cooling rate, it can lead to casting failure in service due to reduced dynamic load capacity (case no.2),
7. Care needs to be taken to avoid excessive air entrainment due to turbulence when pouring at low superheats, to avoid pores (case no.2).
8. The presented procedures, in addition to improving the mechanical characteristics of the finished products, also have an impact on improving the weldability in case of the need for reparative welding, considering that the welding of Hadfield manganese steel is a challenge due to its unique properties.

4. Zaključak

Manganski čelik se intenzivno koristi u rudarskoj industriji i u drugim primenama koje zahtevaju ekstremnu žilavost. Mehanizmi za poboljšanje njegovih svojstava su opšte poznati. Međutim, bez obzira na poboljšanja napravljena radi postizanja boljih svojstava, ako deo otkaže rano u upotrebi, dobitak verovatno neće biti koristan.

Stoga je potrebno obratiti pažnju na sledeće tačke pre puštanja odlivaka u rad, kako bi se garantovao dug vek trajanja:

1. Provera hemijskog sastava nije dovoljan kriterijum da se osigura da odlivci imaju potrebna mehanička svojstva; u principu, to je jedan od nekoliko kriterijuma koje treba kontrolisati tokom proizvodnje (slučaj br. 1),
2. Kontrola mikrostrukture je drugi obavezni kriterijum koji odlivak mora da zadovolji u pogledu oblika i veličine zrna, kao i prisustva drugih faza (slučaj br. 1),
3. Mikrostruktura je konačni zapis parametara procesa livenja (prisustvo inokulanta, temperatura livenja itd.); Ako nisu pravilno odabrani i primenjeni, odlivak ima slabija mehanička svojstva iako je hemijski sastav ispunjen kao uslov (slučaj br. 1 i 2),
4. Mikrostruktura Hadfildovog čelika sa sadržajem hroma u livenom stanju sastoji se od austenitne matrice i legiranog cementita prisutnog uglavnom u obliku lamela,
5. Žarenje je povećalo duktilnost legura u livenom stanju rastvaranjem krtih karbida u austenitnoj matrici,
6. Ako termička obrada nije optimizovana u pogledu temperature rastvaranja, vremena rastvaranja i brzine hlađenja, to može dovesti do kvara odlivaka u upotrebi zbog smanjenog dinamičkog nosivosti (slučaj br. 2),
7. Potrebno je voditi računa da se izbegne prekomerno unošenje vazduha zbog turbulencije prilikom livenja na niskim pregrejavanjima, kako bi se izbegle pore (slučaj br. 2).
8. Prikazane procedure osim poboljšanja mehaničkkih karakteristika gotovih proizvoda imaju uticaj i na poboljšanje zavarljivosti u slučaju potrebe za reparaturnim zavarivanjem, obzirom da zavarivanje Hadfieldovog manganskog čelika predstavlja izazov zbog njegovih jedinstvenih svojstava.

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