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Influence of chromium additions and true strain rate on hardness of austenitic manganese steel

The influence of solution annealing heat treatment on the microstructure and hardness of Hadfield steel containing up to 3.16% chromium and 0.15% nitrogen was investigated. Furthermore, the effects of chromium additions on the hardness and microstructure of austenitic manganese steels in the as-cast and heat-treated conditions have been studied. The true stress-true strain response of nitrogen alloyed austenitic manganese steel with chromium additions in the as-cast and heat treated conditions under compression loading was also studied. The microstructural observations on the as-cast and heat-treated steels with chromium additions revealed the stability of austenite phase in the as-cast state deformation with precipitation of carbides and carbonitrides on the grain boundaries. These precipitates increase by increasing true strain and chromium content.

2^2 factorial design was used to investigate the contribution effect of chromium additions and true strain on hardness of austentic manganese steel as cast and after heat treatment. The contribution of both chromium additions up to 3.16%, true strain rate up to 0.4, and the interaction combination effect of them were determined of cast and heat treated austenitic manganese steel. The regression models were built up to identify the hardness as function in chromium additions and true strain rate of both cast and heat treated austenitic manganese steel.

Introduction

Hadfield's manganese steel is still used extensively, with minor modifications in chemical composition and heat treatment. Many variations of the original austenitic manganese steel have been proposed by variation of carbon and manganese with or without addition of some elements such as Cr, Ni, Mo, V, Ti and nitrogen. Austenitic manganese steel is sometimes referred to as Hadfield's manganese steel. This steel is low strength, high toughness and ductility with high work-hardening capacity, capable of developing excellent wear resistance when surface hardening by cold working.

Detailed studies [1-2] have shown that carbon in these steels has a tendency to segregate to the grain boundaries causing a thin denuded zone, which transforms to martensite on deformation leading to intergranular embrittlement.

Chromium represents the most common element, which employed in Hadfield manganese steel to moderately raise yield strength [3-4]. Also, chromium addition of 1.8 to 2.2% and occasionally as high as 6%, in general reduces the ductility of Hadfield steel by increasing number of embrittling carbides in austenite particularly those containing more than 2.5% chromium. Addition of Cr to Hadfield steel results in carbides surrounding the austenite structure have a lamellar structure. These carbides are richer in Cr and Mn than the austenite grains. After solution treatment, the austenite grains coarsen with decreasing the carbide volume fraction [5].

There is a trend in simulation and modeling of steelmaking and ferroalloys, for example the prediction of magnesium content in production of ferrosilicon magnesium from dolomite, predicted nitrogen solubility in stainless steel, calculation of activation energy in nitriding ferromanganese are illustrated by authors [6-11]. The use of factorial design in steelmaking is relatively limited. Few authors are used it to investigate the effect of different parameters on the metallurgical process. 2^2 factorial design was used to investigate the effect of cooling rate after rolling and cooling rate after coiling on mechanical properties of 65Mn steel grade[12]. Also, the influence of gas ratios H_2/CO on reduction kinetics was investigated [13]. The influence of the presence of iron oxide and / or silicon oxides in manganese ore was investigated by using factorial design[14].

2^3 factorial design was used in investigation the influence of addition of SiO_2, MnO_2 and reaction temperature on reduction degree of synthetic iron ore[15]. 2^4 factorial design was used to investigate the oxidation behavior as function in time, temperature, nitrogen and nickel contents[16]. Also, it was used to analysis the reduction yield of synthetic iron oxide [17].

This study aims to study the effect of chromium additions on the strain hardening rate, compression strength and abrasion resistance of austenitic manganese steel containing 0.15% N. Furthermore, it is aimed to be seen to what extent cold working process affects transformation through microstructure examination. In addition, the effect of solution treatment on microstructure and hardness of high manganese steel containing 3.16% Cr and 0.15% N has been also investigated. Also, the contribution effect of chromium content and

true strain hardening on hardness is investigated for cast steel and also, after heat treatment.

Experiments

Four grades of high manganese steels with base composition of 0.9% C, 14.5-15% Mn, 0.15% N and different Cr contents were melted in 15 kg high frequency induction furnace. The chemical compositions of the raw materials used is given in Table 1. These investigated steels were casted into alumina moulds with 270 mm in length and 55 mm in diameter.

Materials	mass content, %							
	C	Si	Mn	Cr	Al	S	P	N
Steel scrap	0.111	0.05	0.403	-	-	0.014	0.023	-
High carbon ferromanganese	6.52	0.133	76.3	-	-	0.088	0.05	-
Nitrided manganese metal	0.01	-	92	-	-	0.05	0.01	6.1
Fe CrN	2.95	3.0	-	65	-	-	-	6.0
Ferrosilicon	-	75	-	-	1.4	0.01	0.005	-

Table 1: Chemical composition of the raw materials used in the production of modified austenitic manganese steel

Samples for different tests were machined by spark erosion machine. Preliminary experiments were carried out to select the optimum heat treatment condition. For solution annealing of all investigated steels, the specimens were heated in slow rate and soaked at 1080°C for 2 h and then quenched quickly in water. Specimens for compression test were machined in cylindrical shape with diameter 5 mm and length 10 mm. Universal Püf machine (1000 KN) was employed to perform the tests at room temperature (22°C) with strain rate 8.3 x 10-3/s to check repeatability and consistency between results, tests were repeated 3 times. Vickers hardness (HV10) was employed to measure the hardness of cast and quenched specimens. Also, hardness of the compressed specimens were measured at different deformations. Microstructure of the cast, quenched and compressed samples were performed by optical microscope. Wear resistance test was carried out under abrasion condition. Specimens with dimensions 12 x 12 x 8 mm^3 were prepared from the investigated steels. A high stress abrasion wear was performed by pin-abrasion test. The test used 70-mesh alumina abrasive, a 90 N specimen load, and 30 rpm specimen rotation speed. Test duration was 10 minutes. AISI 1020 cold-rolled steel standard was tested with each batch of specimens.

The factorial design was applied on the results of 0%, 1.65% Cr and 3.16% Cr at true strain rates 0% and 0.4 of cast steel and heat treated steels to investigate their effect on hardness. The influence of chromium addition, true strain rate and interaction combination effect on hardness was investigated. Regression models were deduced to calculate the hardness in terms of chromium content and true strain. Interpretation between the predicted values and experimental values were investigated.

Result and discussion

The chemical composition of produced steels are listed in Table 2. The stress-strain tests under compressive loading of investigated as cast and heat treated steels are diagramed in Figures 1 and 2, respectively. They show how the work hardenability characteristics are affected by chromium additions.

In cast condition, addition of 1.65% Cr has no effect on the strain hardening behavior of investigated nitrogen contained Hadfield steel. The true stress-true strain curves for the two free and 1.65% Cr containing steels are very similar. However, further chromium additions of 2.26-3.16% have a significant effect on the compression yield strength and strain hardening behavior of investigated steels. The compression yield strength is strongly increased by increasing chromium addition up to 3.16%. Furthermore, effective increase in compression strength occurs at lower strain for steels containing higher chromium contents. Plastic deformation is needed for the work hardening of the austenite matrix to its maximum strength, but the amount of plastic deformation for steels containing higher chromium content is lower than that what is needed for hardening the investigated Cr-free steel to its maximum value.

The results obtained in Figure 2 clarify the superior high strength high ductility of as-cast N-high manganese steels containing 3.16% Cr.

Comparing the results of stress-strain curves for the investigated steels in the two conditions

Steel No.	mass content, %							
	C	Mn	Si	Cr	Al	S	P	N
HS_0	0.9	15.25	0.6	-	0.025	0.04	0.005	0.15
HS_1	0.89	14.67	0.61	1.65	0.036	0.015	0.005	0.148
HS_2	0.86	14.9	0.66	2.26	0.033	0.02	0.006	0.150
HS_3	0.84	14.56	0.85	3.16	0.032	0.014	0.003	0.149

Table 2: Chemical composition of the produced ingots

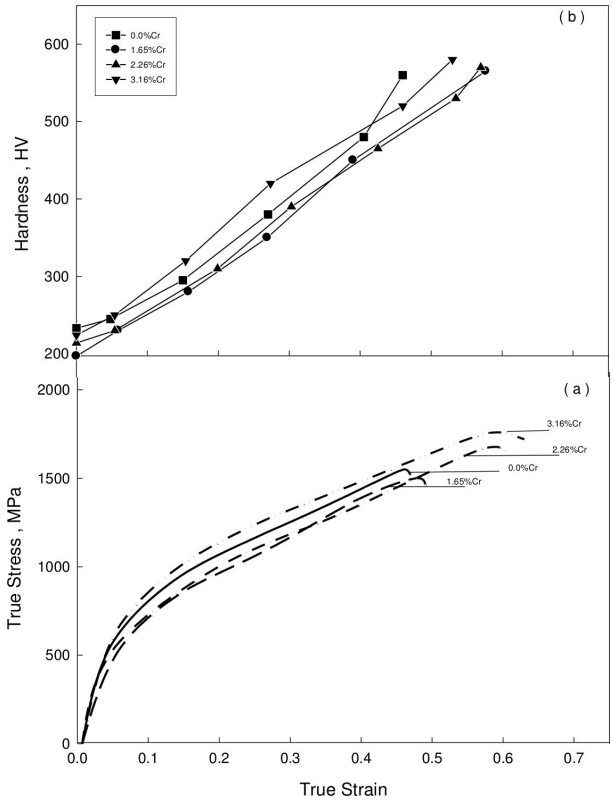

Figure 1: Effect of chromium addition on: (a) true stress-true strain curve, (b) true strain-hardness relationship of as cast

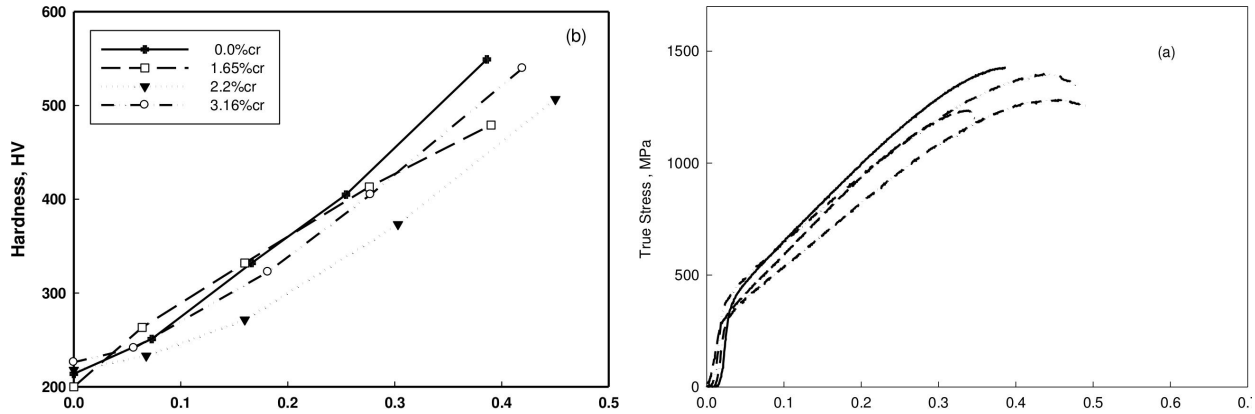

Figure 2: Effect of chromium addition on: (a) true stress-true strain curve, (b) true strain-hardness relationship of heat treated austenitic manganese steel

of as-cast and heat treatment, Figures 1 and 2, illustrates the negative effect of heat treatment on the compression strength of Cr-high manganese steels. The compression strength values of heat-treated Cr-high manganese steels are much lower comparing with that of as-cast steels. For all stages of compression, Cr-steels in cast form have the higher load required for certain strain comparing with heat-treated steels. Furthermore, solution treatment and quenching process of Cr-containing Hadfield steels deteriorates the ductility of these steels. The most important feature of the Hadfield steels is the strong work hardening ability as a result of pressure against the steel surface. This grade of steel can work harden from an initial level of about 200-220 HV to more than 500 HV. This hardening is limited, however, into a thin surface layer of the steel whereas the inner part remains soft and ductile and the whole steel shows a ductile behavior [18]. The prerequisite for this kind of behavior is that the microstructure of the steel is fully austenite without continuous band of carbides at the grain boundaries [18]. Examination of the as-cast conventional Hadfield steel, exhibited the formation of brittle mixed carbides - mainly iron/manganese carbides along austenite grain boundaries and other interdendritic areas due to Mn and C segregation [3-5, 19] and the hole behavior of the steel is brittle. Under the mechanical stresses, the steel breaks along the brittle grain boundaries. Such an as-cast structure should be solution treated to the austenitizing temperature, at a certain holding time, for dissolving the grain boundary carbides into the steel matrix, then water quenching to prevent the precipitation of the carbides and preserve the full austenite structure [3-5, 18-19].

In the present study, the nitrogen combined with chromium additions have been used to examine their effect on the work hardening of Hadfield steels. Chromium has a strong affinity for both carbon and nitrogen [20]. Such addition of carbide and nitride forming elements permits a large quantity of dispersed carbides and carbonitrides to be formed in the melt what provides for production of high quality and fine grain structure with location of the most carbides and carbonitrides inside of grains. The presence of such very hard particles inside the grains promotes steel capability to cold hardening [21].

Metallographic examination of investigated as-cast steels illustrates carbide or carbonitride precipitates on the grain boundaries as illustrated in Figure 3. Increasing the chromium content in these steels leads to the

formation of carbides/carbonitrides inside grains accompanied with increasing of hardness. The microstructure of investigated steels after austenitization at 1080°C and water quenching is illustrated in Figure 3. The microstructure observations reveal coarse austenite and the amounts of carbides/carbonitrides, which were not taken in solution during austenitization, have been increased as Cr content increased.

For as-cast steels, cold working has been carried out up to 0.58 true strain without fracture. This may be explained by the unchangeable structure as the results of cold working as shown in Figure 4. The microstructure reveals austenite grains with the presence of carbides/ carbonitrides on the grain boundaries and inside the grains, which increase with increasing chromium content.

The presence of nitrogen increases the stability of austenite as an austenite former. Nitrogen stabilizes austenite under plastic deformation and preserves its plastic parameters [22]. The work hardening tendency in the as-cast investigated steels is suggested to be improved by using nitrogen as alloying element and introducing separately distributed hard particles into microstructure by alloying with nitrogen and chromium as strong carbide/nitride former. Nitrogen in combination with strong nitride forming elements form hard nitride on the grain boundary zones and partially transforms the grain boundary carbides into carbonitrides [18].

Usually, a fully austenite structure, essentially free of carbides and reasonably homogeneous with respect to carbon and manganese, is desired in the as-quenched condition. This is not always attainable in steels containing carbide forming element such as chromium. In solution treatment of such steels, carbide and carbonitride precipitates formed in the microstructure following casting are partially but not completely dissolved [18].

The heat treatment of investigated steels produced relatively fine dispersion of carbide and carbonitrides in coarse austenite matrix. The coarse austenite matrix of heat-treated steels comparing with that of as-cast steels could be attributed to the grain growth during solution treatment and the tendency of chromium to speed up grain growth rate [5, 23-24]. Large-grained structure with individual inclusions of carbides and carbonitrides at the boundaries of austenitic grains impairs the physico-mechanical properties of the steels, including its liability to cold hardening [21]. Furthermore, the fine dispersed particles may act as nuclei for nucleus growth of martensite transformation.

As indicated in Figure 4., cold working of heat-treated chromium austenitic manganese steels results in almost transformation to induced martensite in deformed austenite grains. This transformation is enhanced either by increasing Cr content or by increasing the percentage of cold reduction. However, there are differences of opinions as to whether martensite can be produced by cold working. The obtained results of investigated heat-treated steels, confirm the possibility of martensite formation by cold working, which agree with other studies [25-27].

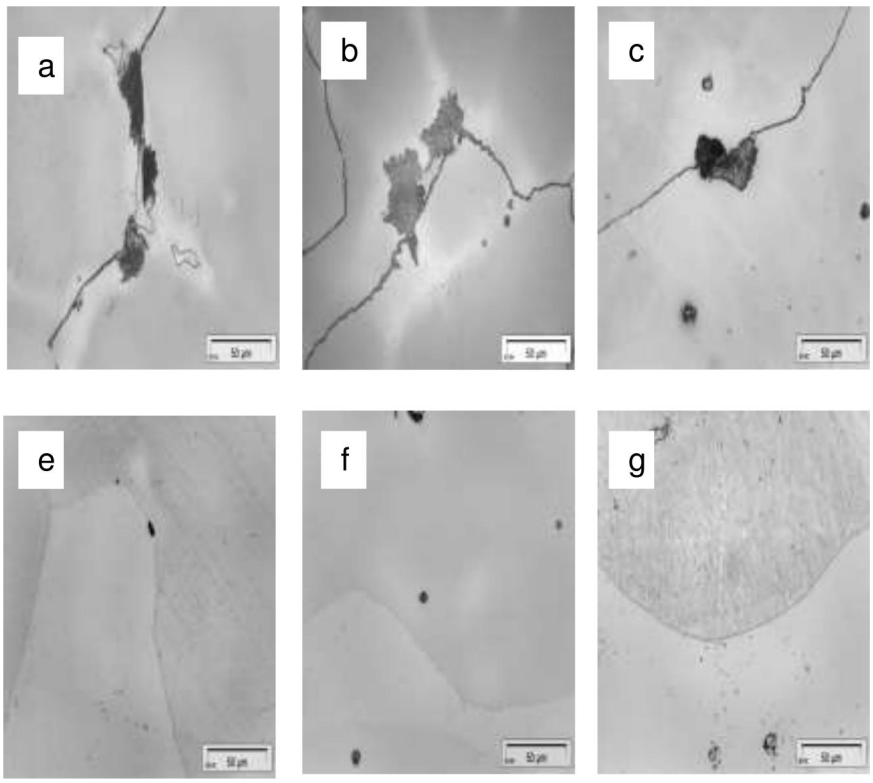

Figure 3: Optical micrograph of as cast and heat treated austenitic manganese steel at chromium contents, a-as cast 1.65% Cr, b-as cast 2.2% Cr, c-as cast 3.16% Cr, e-heat treated 1.65% Cr, f-heat treated 2.2% Cr g-heat treated 3.16% Cr, X=500

Wear resistance. In the present study, the effect of alloying austenitic manganese steel containing 0.15% N with chromium additions on the wear resistance of this type of steels has been investigated. The results of the effect of chromium contents on the relative abrasion wear of the investigated steels are given in Table 3. The relative abrasion wear values has been determined as a ratio of weight loss of the steel sample to weight loss of the standard

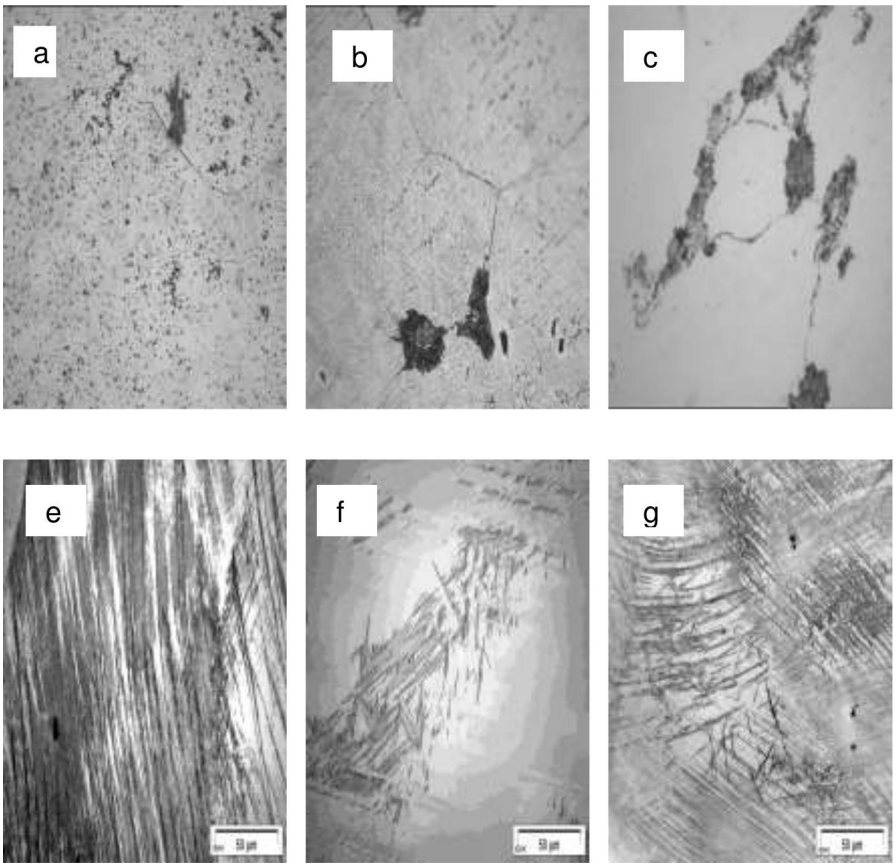

Figure 4: Optical micrograph of as cast and heat treated hadfield steel containing chromium at different strain reduction a-as cast 1.65% Cr at reduction 23.64%, b- as cast 2.26% Cr at reduction 26.1%, c-as cast 3.16% Cr at reduction 41%, e-heat treated 1.65% Cr at reduction 34%, f-heat treated 2.26% Cr at reduction 39%, g-heat treated 3.16% Cr at reduction 37%, X=500.

materials AISI 1020 cold rolled steel. The low relative wear ratio of the investigated steels indicates the high wear resistance of these steels. For both as-cast and heat treated steels, the relative wear ratio decreases by increasing chromium addition up to 3.16%, Figure 5.

Steel No.	Relative abrasion ratio	
	cast state	heat treated state
HS_0	0.240	0.206
HS_1	0.190	0.168
HS_2	0.179	0.165
HS_3	0.167	0.158

Table 3: Effect of Cr addition on relative abrasion factor to high stress grinding on the as cast and heat treated investigated steels

The wear resistance of metal is strongly dependent on its hardness. However, in austenitic steels, initial hardness does not correlate with the abrasion resistance [28]. Furthermore, the amount of abrasion wear is known to be dependent on microstructure, alloying content and second phase particles [29]. Austenite is more resistance to abrasive wear than ferrite, pearlite or martensite. This is mainly due to the ductility and strain hardening capacity of austenite [29]. In addition, at similar hardness, steels with greater amount of carbides or carbonitrides of a higher hardness, will show better resistance to wear [30]. Chromium has a strong affinity for both carbon and nitrogen, and it has a strong tendency to form hard and stable carbides [20]. Chromium carbides are about 65/70 HRC [31].

Increasing chromium content is accompanied by increasing the carbides/carbonitrides contents for both as-cast and heat-treated Cr-containing steels. These embedded carbides/carbonitrides particles are harder than the steel matrix around them and can help prevent the matrix from being worn away resulting in higher abrasion wear resistance. However, comparing with other high hardness carbides particles such as V, Mo and W carbides, Cr carbides because of their relatively lower hardness are among the least effective. Comparing with as-cast steels, the heat treatment has no clear effect on the wear resistance of investigated chromium-containing high manganese steels. The

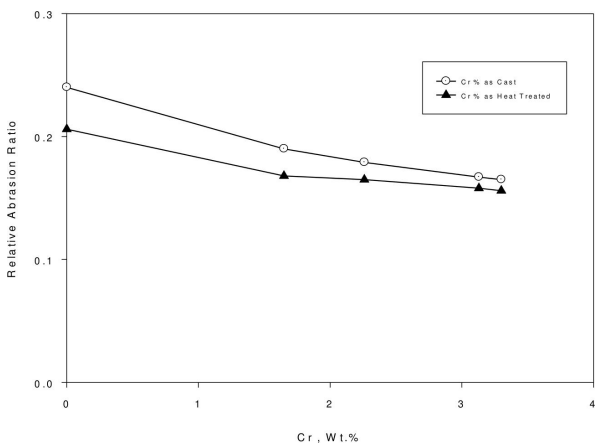

Figure 5: Effect of chromium contents on relative abrasion ratio of the investigated steels

negative effect of large-grained structure of heat-treated steels on wear resistance is equalized with relatively fine dispersion of carbides/ carbonitrides with the results of approximately similar abrasion wear values for both as-cast and heat-treated investigated steels.

Two models were built to cover the range of chromium contents. The first model cover the chromium content up to 1.65% and the second model cover chromium contents start from 1.65% up to 3.16%. Tables 4-5 present the

influence of chromium contents at different true strain rate on hardness of cast steel and heat treated steel.

Symbol effect	Chromium addition, wt. %	True strain rate	Hardness, HV	
			As cast	Heat treated
(1)	0	0	234.6	225.7
A	1.65	0	200	200
B	0	0.4	480.1	549.9
AB	1.65	0.4	451.3	478.7

Table 4: True strain rate and chromium addition effect on hardness.

Symbol effect	Chromium addition, wt. %	True strain rate	Hardness, HV	
			As cast	Heat treated
(1)	1.65	0	200	200
A	3.16	0	226.5	226.8
B	1.65	0.4	451.3	478.7
AB	3.16	0.4	519.3	510.2

Table 5: True strain rate and chromium addition (1.65 – 3.16%) effect on hardness.

Let we donate the high chromium content (1.65%) at low true strain rate by "A", high true strain rate (0.4) at 0.0% Cr is denoted by "B", high chromium content (1.65%) at high strain rate is denoted "AB" and low chromium content 0% Cr at "0.0" true strain rate is denoted by "1". Complete analysis of chromium content and true strain rate on hardness was illustrated as given in Table 6 of cast and heat treated steels.

The factorial design in 2^2 was applied to investigate the contribution effect of chromium content and true strain rate on hardness of cast and heat treated austenitic manganese steel. The four treatment combinations in the design are usually represented by lowercase letters. The high level of any factor in the treatment combination is denoted by the corresponding lowercase letter and that the low level of a factor in the treatment combination is denoted by the absence of the corresponding letter. Thus, "a" represents the treatment combination of A at high level and B at low level, "b" represents A at low level and B at high level, "ab" represents both factors at the high level and (1) is used to denote both factors at low level.

The average effect of any factor can be defined as the change in response produced by a change in the level of that factor averaged over the levels of the other factor. This is illustrated elsewhere [16-21]. The main effect of A, B, and AB can be calculated as given in Equations (1-3).

$$A = \frac{1}{2n}\{[ab - b] + [a - (1)]\} = \frac{1}{2n}[ab + a - b - (1)] \quad (1)$$

$$B = \frac{1}{2n}\{[ab - a] + [b - (1)]\} = \frac{1}{2n}[ab + b - a - (1)] \quad (2)$$

$$AB = \frac{1}{2n}\{[ab - a] - [a - (1)]\} = \frac{1}{2n}[ab + (1) - a - b] \quad (3)$$

Based on the 2^2 factorial design analysis the average effect of A, B, and their combination effect (AB) on hardness can be calculated. The results are tabulated in Table 6.

The calculation of factorial design of cast steel in chromium range up to 1.65% shows that the true strain rate has positive significant effect on hardness while chromium addition has small negative effect on hardness. The inter-combination effect of chromium additions and true strain rate is small and positive and can be neglected. This means that as true strain hardening increases the hardness of cast austenitic manganese steel increases in chromium range up to 1.65%.

While as true strain rate increases the hardness decreases of cast austenitic manganese steel within chromium content up 1.65%. The interaction combination of true strain rate and addition of chromium is very small and positive which can be neglected. The hardness can be determined as a function in true strain rate and chromium additions as given in Equation (4). Figure 6 shows the variation between the calculated hardness from regression model and the measured hardness.

$$Hardness = 234.6 - 20.9696 * a + 613.75 * b + 8.7878 * a * b \quad (4)$$

Where hardness is in HV, "a" is chromium content in wt. %, and "b" is true strain rate.

Fig. 6 shows that there is no difference between the predicted hardness of cast steel (0.0 – 1.65% Cr) according to Equation (4) and

As cast 0.0-1.65%Cr			As cast 1.65-3.16%Cr		
Affecting Factor	Average effect	Magnitude effect	Affecting Factor	Average effect	Magnitude effect
A	-31.7	18.98868	A	47.25	39.53912
B	248.4	1165.948	B	272.05	1310.753
AB	2.9	0.158918	AB	20.75	7.625347
Heat treated 0.0-1.65%Cr			**Heat treated 1.65-3.16%Cr**		
Affecting Factor	Average effect	Magnitude effect	Affecting Factor	Average effect	Magnitude effect
A	-48.45	37.71023	A	29.15	14.62779
B	301.45	1459.83	B	281.05	1359.781
AB	-22.75	8.314468	AB	2.35	0.095069

Table 6: Contribution effect of A, B, and AB on hardness of cast and heat treated steel at different chromium ranges.

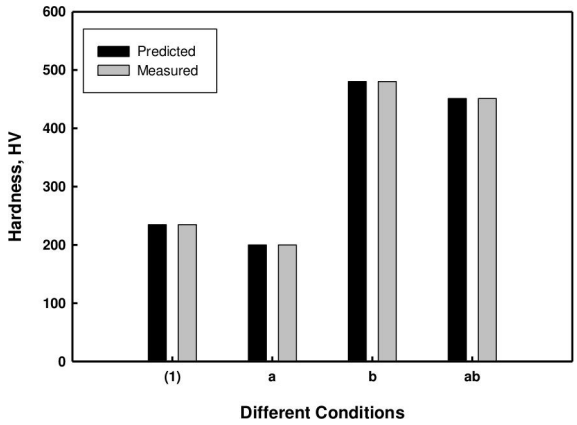

Fig. 6 : The variation between the predicted and measured hardness of cast steel (0.0 – 1.65% Cr)

measured hardness. Equation (4) is used to predict the hardness at different true strain rate of cast steel of 0.0% and 1.65% Cr as given in Figures 7-8 respectively. These figures show that there are an agreement between the predicted and measured hardness to large extent.

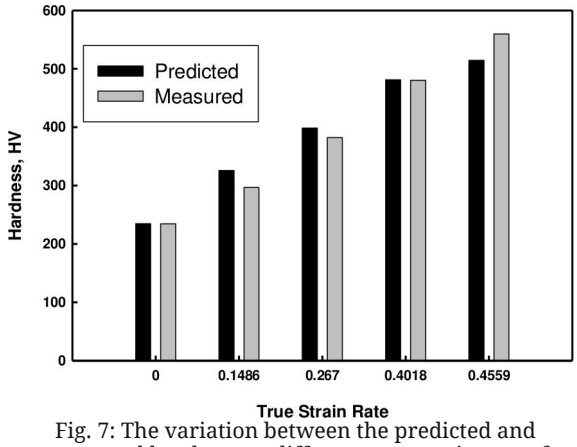

Fig. 7: The variation between the predicted and measured hardness at different true strain rate of cast steel free chromium

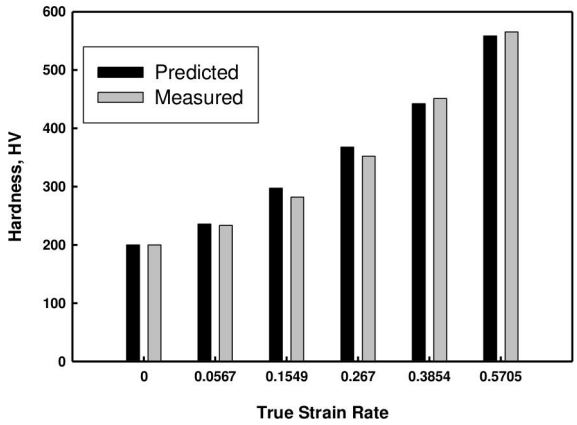

Fig. 8: The variation between the predicted and measured hardness at different true strain rate of cast containing 1.65% Cr

The calculation of factorial design shows (as illustrated in Table 6) that both the true strain rate and addition of chromium in range 1.65 – 3.16% have positive effect on hardness of cast austenitic manganese steel. These mean both true strain rate and addition of chromium (in range 1.65 -3.16%) cause an increasing in hardness. Also, the interaction combination effect of true strain rate and chromium additions (in range 1.65-3.16%) has small positive effect on hardness. The hardness of cast austenitic manganese steel (chromium range 1.65 – 3.16%) can be predicted as a function in true strain rate and addition of chromium by using regression model as given in Equation (5). The variation between the predicted and measured hardness is presented in Figure 9.

$$Hardness = 225.8 - 15.6969 * a + 810 * b - 68.33 * a * b \quad (5)$$

Where hardness is in HV, “a” is chromium content in wt. %, and “b” is true strain rate.

Figure 9 shows that the predicted hardness – according to Equation 5 – is identical with the measured hardness of cast steel (1.65 – 3.16% Cr). Equation 5 is used to predict the hardness at different true strain rate of cast steel of 1.65% Cr, 2.2% Cr and 3.16% Cr and presented in Figures 10 – 12 respectively. Figures 10-12 illustrated that the predicted hardness is nearly equal the measured one at different true strain rate of austenitic manganese steel containing 1.65% Cr, 2.2% Cr and 3.16% Cr respectively.

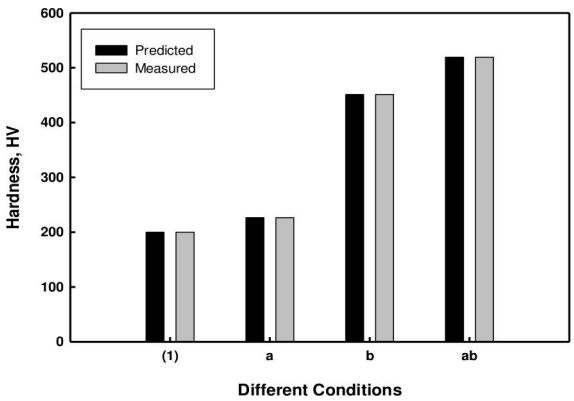

Fig. 9: The variation between the predicted and measured hardness of cast steel (1.65 -3.16% Cr)

The chromium addition of heat treated austenitic manganese steel has negative influence on hardness while the true strain rate has positive large influence on hardness. That is mean that the hardness increase as the true strain increase and as the addition of chromium decreases in range up to 1.65%. The interaction combination of chromium addition (up to 1.65%) and true strain rate (up to 0.4) has negative influence on hardness as given in Table 6. The hardness can be predicted as a function in true strain rate and chromium additions by using regression model as given

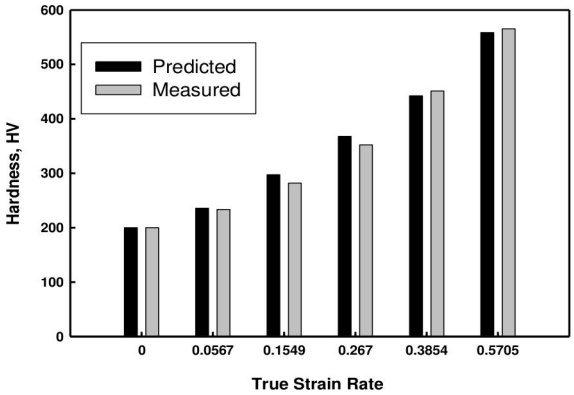

Fig. 10: The variation between the predicted and measured hardness at different true strain rate of cast steel containing 1.65% Cr

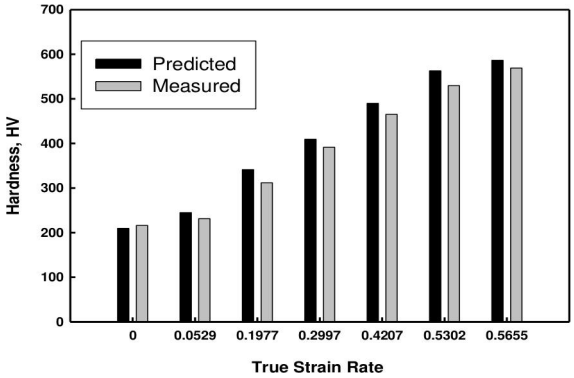

Fig. 11: The variation between the predicted and measured hardness at different true strain rate of cast steel containing 2.2% Cr

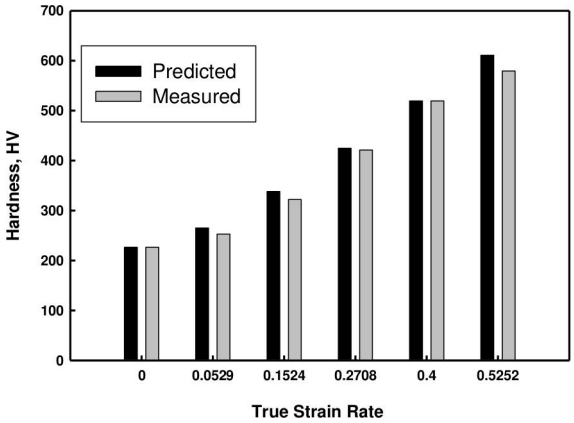

Fig. 12: The variation between the predicted and measured hardness at different true strain rate of cast steel containing 3.16% Cr

in Equation 6. The variation between the calculated and measured hardness is illustrated in Figure 13.

$$Hardness = 171.04 + 17.5497 * a + 514.881 * b + 68.71 * a * b \quad (6)$$

Where hardness is in HV, “a” is chromium content in wt. %, and “b” is true strain rate.

Figure 13 shows that the predicted hardness – according to Equation 6 – is identical with the measured hardness of heat treated steel (up to 1.65% Cr). Equation 6 is used to predict the hardness at different true strain rate of heat treated steel of 0.0% Cr and 1.65% Cr and presented in Figures 14-15 respectively. Figures 14-15 showed that the predicted hardness is in an agreement with the measured to certain extent of heat treated austenitic manganese free chromium and containing 1.65% Cr respectively.

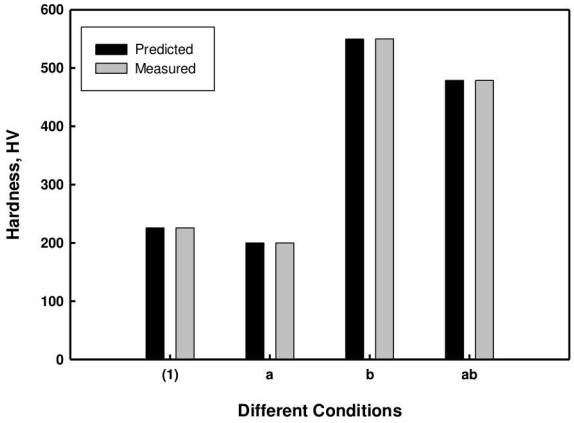

Fig. 13: The variation between the predicted and measured hardness at different true strain rate of heat treated steel containing up to 1.65% Cr

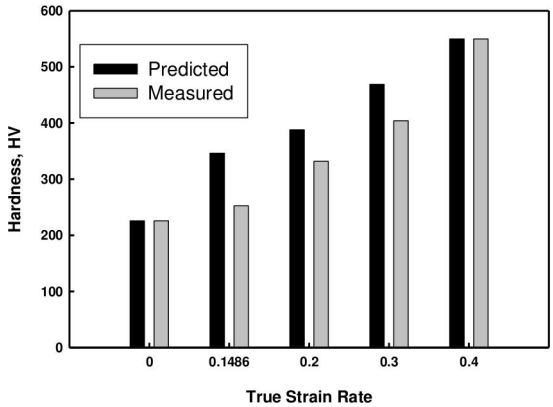

Fig. 14: The variation between the predicted and measured hardness at different true strain rate of heat treated steel free chromium.

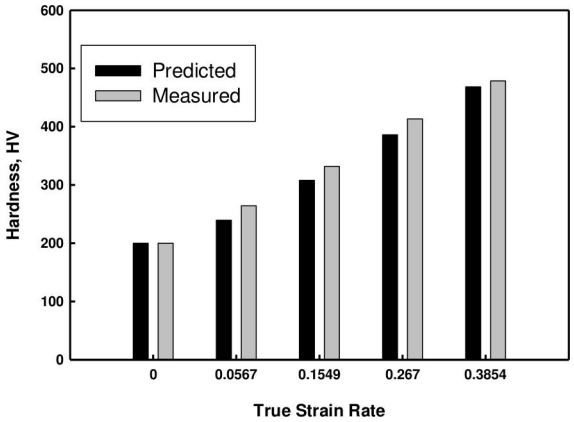

Fig. 15: The variation between the predicted and measured hardness at different true strain rate of heat treated steel containing 1.65% Cr

The calculation of factorial design shows that both the chromium additions (in range 1.65 -3.16%) and true strain rate have positive

influence on hardness of heat treated austenitic manganese steel. This means that the hardness increases as the true strain rate and / or chromium addition increases. Also, the interaction combination effect (AB) has little positive effect which can be neglected. The true strain rate contribute in increasing hardness by more than 95 times of contribution of chromium additions as shown in Table 6. Hardness can be predicted as a function in both true strain rate and chromium additions (1.65-3.16%) by using regression model as given in Equation 7. Figure 16 represents the variation between the predicted and measured yield strength.

$$Hardness = 170.715 + 17.748 * a + 683.91 * b + 7.781 * a * b \quad (7)$$

Where hardness is in HV, “a” is chromium content in wt. %, and “b” is true strain rate.

Fig. 21 shows that the predicted hardness – according to Equation 7 – is identical with the measured hardness of heat treated steel (containing chromium from 1.65% to 3.16%). Equation 7 is used to predict the hardness at different true strain rate of heat treated steel

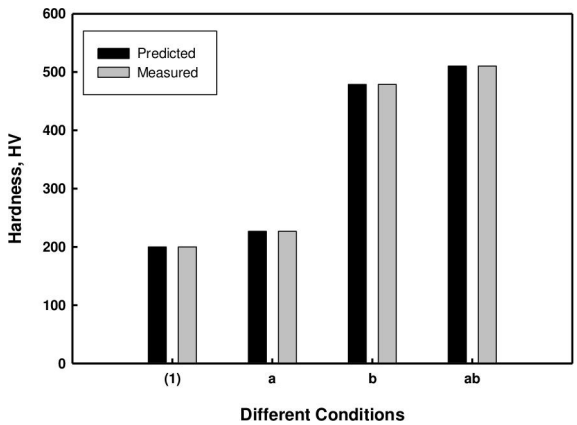

Fig. 16: The variation between the predicted and measured hardness at different true strain rate of heat treated steel (1.65 -3.16% Cr)

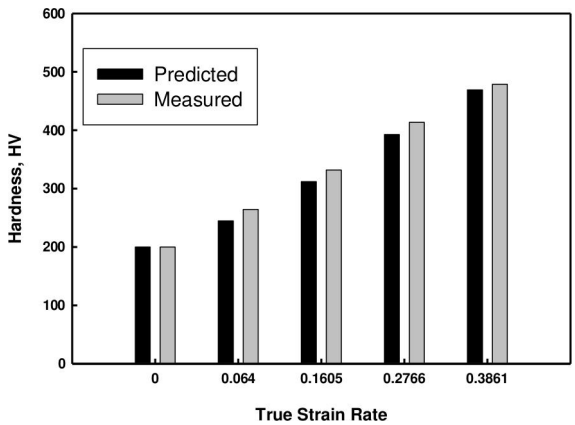

Fig. 17: The variation between the predicted and measured hardness at different true strain rate of heat treated steel containing 1.65% Cr

of 1.65% Cr, 2.2% Cr and 3.16% Cr. The predicted and measured data is presented in Figures 17-19 respectively. Figures 17-19 showed that the predicted hardness is in an agreement with the measured to certain extent of heat treated austenitic manganese containing 1.65% Cr, 2.2% Cr and 3.16% Cr respectively.

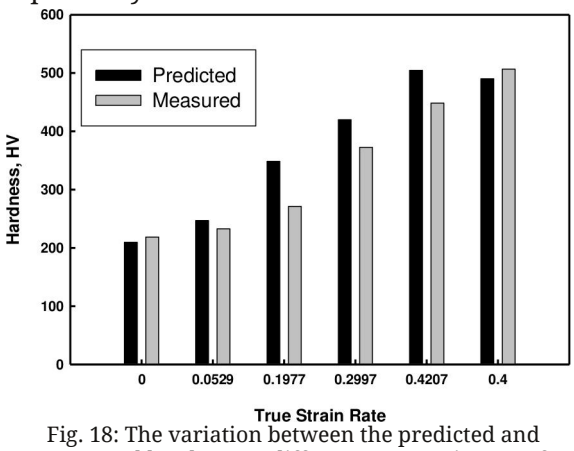

Fig. 18: The variation between the predicted and measured hardness at different true strain rate of heat treated steel containing 2.2% Cr

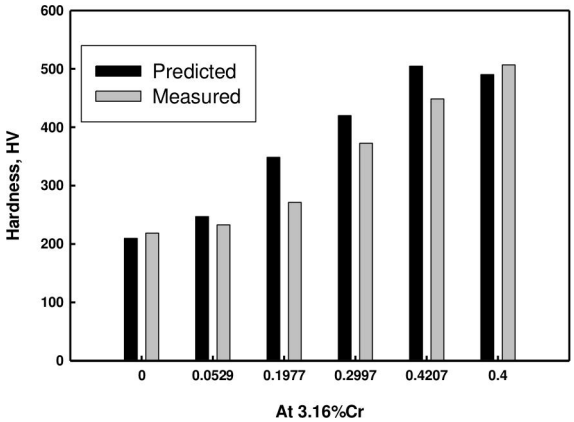

Fig. 19: The variation between the predicted and measured hardness at different true strain rate of heat treated steel containing 3.16% Cr

Conclusions

Based on this work carried out to investigate the effect of single addition of chromium on high manganese steel containing 0.15% nitrogen, the following conclusions are drawn:

In cast-condition, addition of 1.65% Cr has no effect on strain hardening behavior of this steel. Further chromium additions of 2.26-3.16% have a significant effect on the yield strength and strain hardening behavior. The compression strength values of heat-treated Cr-steels are much lower comparing with that of as-cast Cr-steels. Strain hardening of heat-treated Cr-steels is accompanied with martensite formation, whereas as-cast Cr-steels retain their basic austenite microstructure even after severe cold working. For both as-cast and heat-treated steels, the abrasion wear resistance increases by

increasing the Cr-addition up to 3.16%.

The effects of true strain rate has positive significant effect over chromium range up to 3.16 for cast and heat treated austenitic manganese steel. The addition of chromium up to 1.65% has negative effect on hardness for both cast and heat treated austenitic manganese steel. The negative effect of chromium additions in heat treated steel is greater than in cast steel. The addition of chromium from 1.65% Cr to 3.16% Cr has positive effect on hardness for both cast and heat treated austenitic manganese steel. The positive effect of chromium additions in heat treated steel is smaller than in cast steel. The interaction combination of true strain rate and chromium additions of cast steel (0.0 -1.65% Cr) and heat treated steel (1.65 – 3.16%) are positive and small and can be neglected. The interaction combination of true strain rate with chromium additions is positive in cast steel (1.65-3.16%) and negative in heat treated steel (0.0 – 1.65). The hardness can be predicted as a function in true strain rate and chromium additions for both cast and heat treated steel within two interval of chromium contents. It was found that the predicted values are very close to the measured values, which means factorial design is very useful technique in the field of steel and it is be recommended to be used in several processes in metallurgy.

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