[1.] **J. O. AGUNSOYE,** [2.] **S. I. TALABI**

PROPERTIES OPTIMIZATION OF HADFIELD AUSTENITIC MANGANESE STEEL CASTING

[1.] Department of Metallurgical and Materials Engineering, University of Lagos, Akoka, NIGERIA
[2.] Department of Materials and Metallurgical Engineering, University of Ilorin, Ilorin, NIGERIA

Abstract: The properties of Austenitic Manganese Steel (AMnS), used for rock drilling, was optimized as a highly cost efficient and preferment material for the mining industry. To achieve this, inter-critical annealing and homogenization heat treatments operations were employed. Subsequently, relationships were established between various process parameters, mechanical properties, microstructure and alloying elements. Emphasis was given to the control of grain size and phases, most particularly secondary carbides. Hardness, impact and microscopy investigations were carried out on the heat treated samples. The results show an improvement in hardness and impact characteristic of the AMnS. The microstructures of the heat treated samples show substantial grain refinement and a uniform dispersion of secondary carbides along grain boundaries.
Keywords: Carbides, impact, hardness, heat treatment

1. INTRODUCTION

It was the need for an alloy that combines hardness and toughness that motivated Sheffield Robert Abbott Hadfield to embark on the study of alloys of Iron and other elements in 1878. Four years later, he found that with10%Mn, heat treatment and water quenching, the materials have both hardness and toughness. Austenitic manganese steels offer the best combination of toughness and resistance to high stress and gouging abrasion.

Mn steels are simple and cheap to produce and offer excellent potential to replace expensive chromium iron alloy, which are known to possess high hardness and wear resistance but also to show critical limitations regarding ductility and toughness.

The high carbon content in Manganese steels can be completely retained in solution, which provides best resistance to abrasion. Manganese steels generally exhibit freezing ranges as wide as 200°C (temperature range between liquidus and solidus lines), making them susceptible to micro-porosity and the occurrence of deleterious continuous carbide networks, particularly at grain boundaries. During industrial production of manganese steel like many other alloys steel, there is always slight, un avoidable variation in composition for reason ranging from prolong holding of molten bath at high temperature, heavy oxidation characteristic of alloying elements in the shop floor etc. From the Manganese steel equilibrium diagram, a carbon composition greater than 1.2% encourages the formation of acicular carbide which in turn can lead to intergranular embrittlement in steel.

Structural phase transformation has been generally agreed has one of the routes for enhancing materials properties. Similarly, the properties of Hadfield Austenitic Manganese steel can be optimized through the interplay of heat treatment and controlled cooling. A homogenization heat treatment that allows dissolution of carbides and redistribution of chromium and carbon atoms within the iron-manganese matrix will improve AMnS properties. The final material then possesses a homogenized microstructure and uniform wear properties. In the heat treatment process, the austenite grain size before quenching is tremendously influenced by diffusion phase transformations and precipitation. It has been confirmed too that grain size in austenitic manganese steel is primarily a function of the pouring temperature of the casting and section size [2]. Hence, choosing the right temperature is of great important to the performance of the steel in service.

Research has been carried out to get better understanding and controlling of the austenite grain size during the austenitenization process of Mn-steel over the past half a century [1-5]. Even if the austenite grain size is fine after the reverse transformation during heat-up to the single phase austenite region, the grain refinement can easily be hindered due to the high energy zones created by the heterogeneous nature of the second phase carbides re-precipitation in the microstructure [2]. However, microstructural phase transformation through the interplay of heat treatment operations still remains the best route for enhancing the properties of Hadfield Austenitic Manganese steel.

Therefore, heat treatment operations were designed and employed to optimize the properties of specific AMnS compositions. Relationship was established between chemical composition, heat treatments, microstructure and mechanical properties of the produced samples.

2. MATERIALS AND METHODOLOGY

The charge make-up for the melt consist of Mn-Steel foundry returns(1.1%C, 0.64%Si, 12.4%Mn, 1.2%Cr, 0.006%S, 0.005% P and 84.65%Fe), Steel (0.15%C, 0.25%Si, 0.42%Mn, 0.005%S, 0.005%P and 99% Fe), High Carbon Ferro Manganese (0.23%C, 85%Mn), Medium Carbon Ferro Chromium (0.5%C, 70%Cr), Ferro Silicon (0.01%C, 72%Si) and Graphite Powder (99%). The experiment on wear characteristics of the austenitic manganese steel composition was conducted using industrial approach.

2.1. Industrial Scale Experiment

380 Kg of manganese returns with 482 Kg steel scraps, 15 Kg Ferro-chrome, 110 Kg Ferro-manganese, graphite powder 10 kg and 3 Kg Ferro-silicon were melted in a 1-ton capacity induction furnace to obtain the desired composition in accordance with ASTM128C standard. The quantity and chemical composition of the charge make-up are shown in Table I. The molten metal was used to manufacture 500kg jaw plate for the industrial scale test. The molten metal was poured at 1400 $\pm$ 20 °C into an improvised CO_2 moulds, and allowed to solidify to below 150ºC, a temperature below which austenite transformation is halted. After solidification in the mould, the castings were knocked out of the sand mould, short-blasted, and fettled to the required shape and size as shown in Figure 1.

Figure 1. A Locally Produced 500kgamns Jaw Plate in the Factory

The finished casting after heat treatment was taken to Frederick Parker Crusher operating at 200 revolutions per minute in Ratcon construction Quarry located along Lagos-Ibadan express-way, Nigeria, for wear test. Two other castings of known compositions were also subjected to test on the same crusher. The tonnage discharged from the test crusher was measured by the stopping of all the other crusher, and by allowing the discharge belt to run until it carried only the product from the test crusher from the three jaw plates. The belt was then stopped, a linear meter was cleared right across the width of the belt, and the sample collected was weighed.

Admittedly, this is not an ideal procedure for tonnage measurement but it was the only practicable technique available and is one that is commonly employed in the Quarry in Ibadan, Nigeria. The tonnage of aggregate stone crushed by the crusher jaw plates were used to evaluate the wear performance of the manganese steel castings. The result from the crushed aggregate stone is presented in Figure 2.

2.2. Laboratory Scale Experiment

» **Materials and Methods**

The remaining molten metal used for the industrial scale experiment was used to produce balls with a diameter of 104mm as well as rectangular cross-section bars of dimensions25x25 x150mmin Nigerian foundries limited Lagos, Nigeria. The material so produced, were used to investigate the effect of different temperatures through solution hardening heat treatment with view to projecting and predicting the wear characteristic of austenitic manganese steel through its hardenability profile.

Balls and bars were both subjected to inter-critical annealing and homogenization heat treatment. For inter-critical annealing, the samples were heated to 750ºC and 1050 °C, at 750ºC/hr, held for 1 hr for every 25.4 mm section thickness and allowed to cool down in the furnace to a temperature below 150℃. Homogenization heat treatment was carried out by heating the samples to temperature of 750℃ and 1050℃ for 25. 4mm per hour and then water quenched to room temperature in a tank with 2 hp water pump. The bar samples were machined to standard Jominy specimen for hardenability tests. For the determination of the microstructure, samples were cut at different distances (quenched face, middle and far end of Jominy samples). The samples were ground with Tegrapol-31, polished using a colloidal suspension of 0.04μm silicon dioxide and then etched with100mL alcohol and 3mLHNO₃acid after polishing.

» **Impact test**

The effect of three quenching media (which might adversely influence impact strength) on the impact property of the test samples was examined. The cast rectangular bars were machined into standard samples size of 10mmx10mmx50mm with 2mm v-notch for the impact test. The test was carried out at room temperature using a Charpy type an impact testing machine. The tests were carried out with an initial energy of hammer 30kg.m at a striking velocity of 5.6m/s. Impact test results for three quenching media is presented in Figure 8.

3. RESULTS AND DISCUSSION

The charge make-up for the Hadfield Austenitic Manganese Steel is shown in Table I. The chemical composition of the produced Mn-Steel sample is shown in Table II.

Table I. The Estimated Charge Make-up for Hadfield Austenitic Manganese Steel

Charge	Charge Weight (kg)	C	Si	S	P	Mn	Cr	Fe
Returns	380.00	0.04180	0.24320	0.00200	0.00200	4.71200	0.45600	Bal
Steel	482.00	0.07230	0.12050	0.00241	0.00241	0.20240	-	Bal
Fe-Cr	15.00	0.00750	-	-	-	-	1.05000	
Fe-Mn	110.00	0.02530	-	-	-	9.35000	-	
Fe-Si	3.00	0.00003	0.21600	-	-	-	-	
Graphite	10.00	0.95800	-	-	-	-	-	
Total	1000	1.10000	0.57970	0.00441	0.00441	14.26440	1.50600	

Table II. Chemical Compositions of the Experimental Mn- Steel (wt %)

C	Si	S	P	Mn	Cr	Fe
1.10000	0.57970	0.00441	0.00441	14.2644	1.50600	Bal

The industrial wear performance of the newly modified AMnS is presented in Figure 3 along side with an old specification from the same local factory and another imported specification. The percentage of foundry return in the old spec was reduced from 80% to less than 50% in the new modified spec. This appears to have a significant effect on the material performance. The old spec containing 80% foundry return produced the lowest tonnage of crushed aggregate stone. This may be strongly connected to the amount of residual inclusions built up as a result of continue recycled scrap. This argument is substantiated with heavy network of inclusions as seen in the micrograph of the old spec Figure 2 [1].

The impact energy obtained under three different quenched media is shown in Figure 3. The water quenched sample gives the highest impact energy, followed by the air cooled sample impact while furnace cooled sample produced the lowest impact
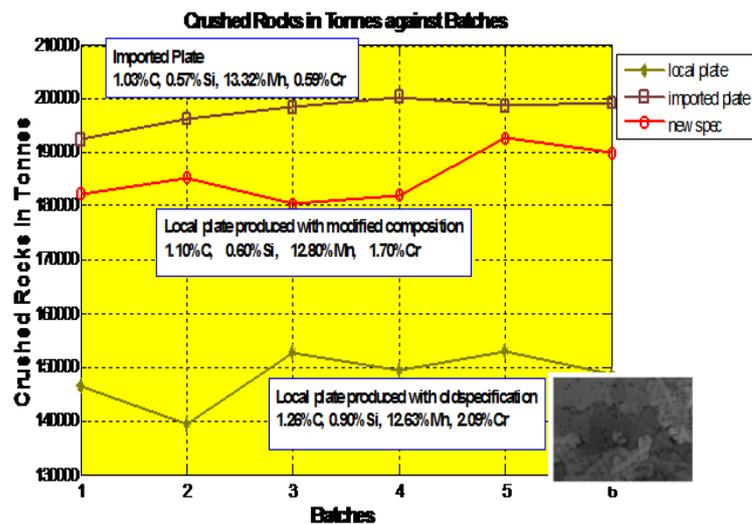
Figure 2. Comparative Output of Crushed Rock for Three Compositions: (b) Microgragh of old spec

result. These behaviors can be explained from the isothermal transformation curve, since water quenched sample gave the fastest cooling rate, the cooling time is sufficiently small to avoid the nose of the curve and prevent chromium carbide reprecipitation. Substantial part of carbon is successfully trapped within the (Fe-Mn)C matrix. The resulting micrograph in Figure 4.a shows a homogenous single phase austenite. This structure upon severe impact encourages metastable austenite-martensite transformation, with good work hardenbility and better wear resistance.
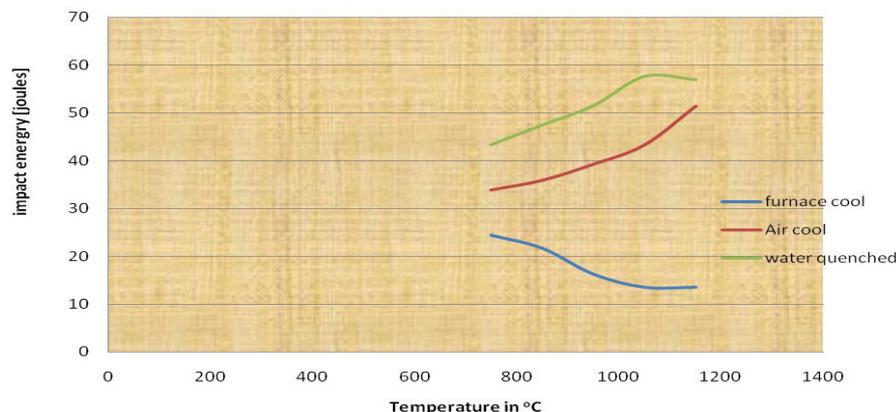
Figure 3. Impact Energy against Heat Treatment Temperature under Different Quenched Media

Air cooled manganese steel sample take longer time to cool, by so doing, sufficient time is allowed for reprecipitation of chromium carbide clustering along the grain boundary. The presence of cluster carbide renders the microstructure inhomogenous (Figure 4.b). Hence, upon severe impact, the stable carbide is not able to transform to martensite. This will lead to poor wear life and in extreme cases, material failure. Furnace cooled manganese steel allow for substantial carbide reprecipitation as seen in Figure 4.c. This microstructure contained large amount of embrittle carbide and it is of little or no engineering application [7]. It can be conclude that annealing of manganese steel by furnace cooling is a systematic way of re-introducing the undesirable embrittling intermetallic within its microstructure.
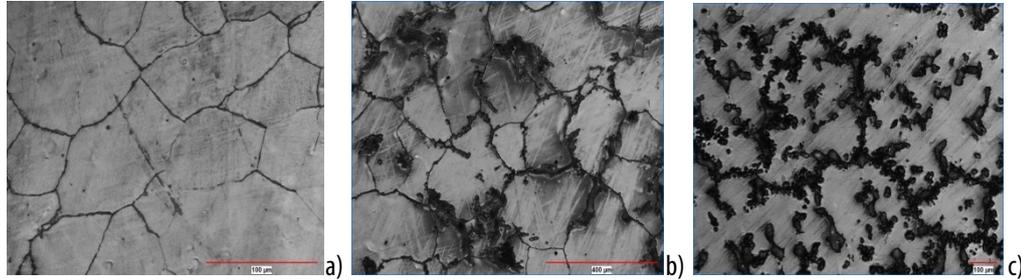
Figure 4. Micrographs of (a) Water Quenched Manganese Steel (b) Air Quenched Manganese Steel (c) Furnace Cooled Manganese Steel

The optical micrographs in Figure 5 and Figure 6 shows the microstructures of the quenched Jominy samples of manganese steel held at 750°C and 1050°C respectively. The microstructure of the Jominy samples contains undissolved chromium-carbides. The undissolved chromium-carbides increase from the quenched face (faster cooling) towards the farthest sample end (slower cooling). The chromium carbide at this temperature was largely heterogeneous and brittle in nature.
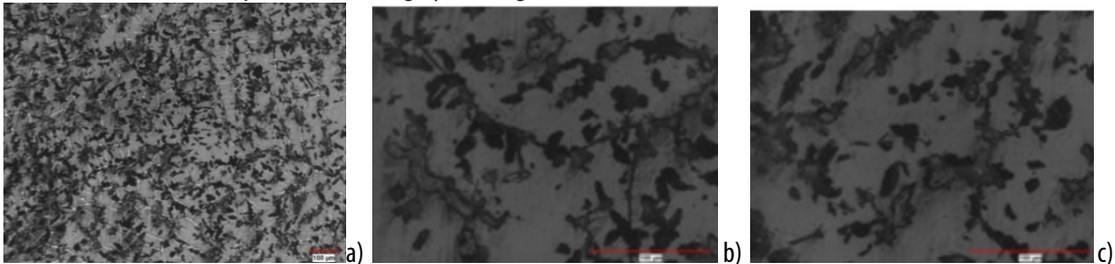
Figure 5. Micrographs of manganese steel at 750°C (a) QuenchedJominy surface (b) 50mm from quenched Jominy surface (c) 100mm from quenched
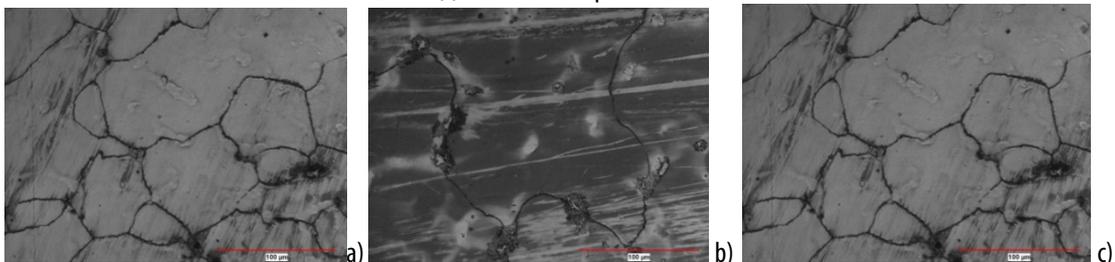
Figure 6. Micrographs of manganese steel at 1050°C (a) Quenched Jominy surface (b) 50mm from quenched Jominy surface (c) 100mm from quenched

However, the Jominy samples show relatively high hardness across the complete length (Figure 9-11). This means that even for relatively slow (which can be assumed to be a typical air cooling), significant hardenability can be achieved. It is important to note that, even the as cast Jominy sample shows a relatively high hardness close to all heat treated Jominy samples. This implies that the chosen sample dimensions provide cooling rates that lead to sufficient hardness across the samples. However the optical micrographs in Figure VII show a slightly different behavior for the   ball sample at 750°C. Due to the faster cooling rate at the surface, the ball show maximum hardness values in the outmost layers. As the cooling rate drop towards the ball center, lower hardness values are measured in the center. This observation is complimented by the microstructural variation of the ball from the quenched surface to the ball core as observed in Figure 8.

Chromium carbide dissolution was achieved for a 104 mm diameter ball held at 1050°C for 1 hour. Quenching in agitated water from this temperature does not lead to any noticeable re-precipitation of the carbides. The relative high hardness observed with Mn-steel at 750°C is indicative of the large proportion of undissolved carbide, it is therefore not a suitable temperature for the heat treating Mn-steel as seen from the micrograph a and b in Figure 1. On the contrary, about 95% of the carbide at 1050°C had dissolved and very little carbide reprecipitation were noticeable along the entire 104mmdiameter ball (equivalent to 4" thick casting). The reprecipitation does agree with Papworth and Williams' work [8].
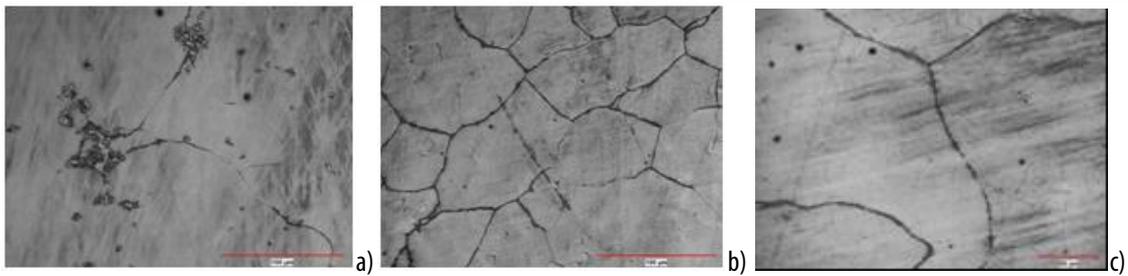
Figure 7. Micrographs of manganese steel at 750ºC (aBall center) (b) 26mm from ball surface (c) Quenched ball surface
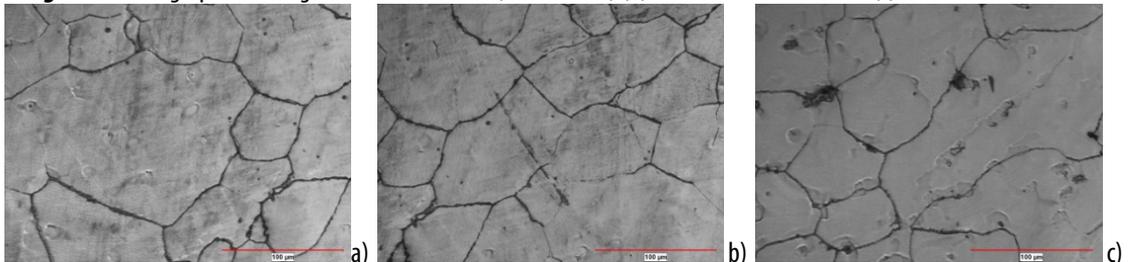
Figure 8. Micrographs of manganese steel at 1050°C (aBall center) (b) 26mm from ball surface (c) Quenched ball surface

There appear to exist a strong relationship between the hardenability band of Austenitic manganese steel with the degree of microstructural homogeneity as the heat treatment temperature increases. Furthermore, the band can be use as a quality control check to forecast the hardness and the likely microstructure of Austenitic manganese steel casting provided the composition is within the limit examined for any section thickness less than 104 mm.
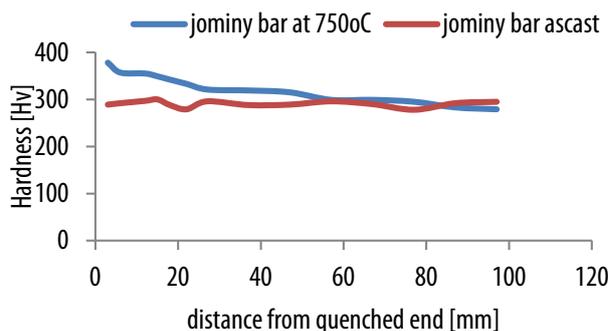
Figure 9. Hardness profileof Jominy bar at 750℃
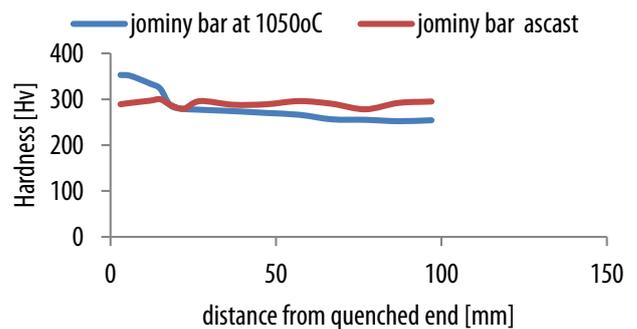
Figure 10. Hardness profile of Jominy bar for Mn-Steel at 1050ºC
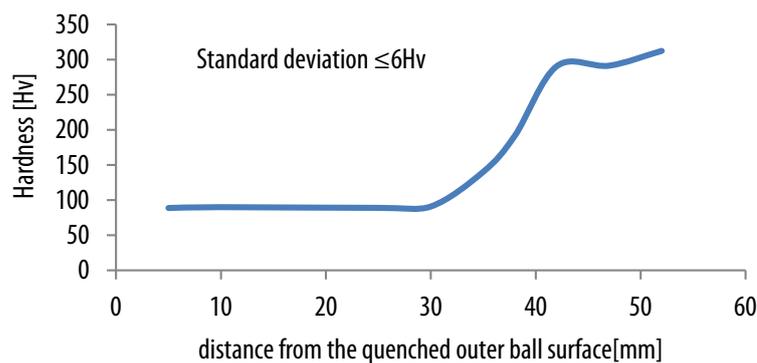
Figure 11. Hardness for 104mm diameter ball water quenched from 750 ℃

4. CONCLUSION

This paper shows that detrimental Cr_3C carbides was precipitated in the investigated Mn steel composition poured at $1400 \pm 20°C$. However, the designed homogenization heat treatment programme helps to dissolve those carbides and/or redistribute them within the Mn-Fe matrix. Samples which were heated to 1050 ℃, soaked for 1 hour and quenched in agitated water shows a completely homogenized microstructure compared to the samples heat treated at750 ℃. Annealing of the AMnS by furnace cooling is not an effective heat treatment operation as it re-introducing the undesirable embrittling intermetallic within the microstructure of the alloy. Also, the performance of the as-cast AMnS casting was strongly influenced by the constituents of the charge makeup composition i.e foundry return in the charge make up. The foundry return in the charge make up should be kept below 50% of the total charge make up. This percent include the return contained in back charging exercise.

References

[1.] Agunsoye, J.O., Talabi, S.I., Abiona, A. A.: On the comparison of microstructure characteristics and mechan-ical properties of high chromium white iron with the hadfield austenitic manganese steel, Journal of Minerals and Materials Characterization and Engineering, 1, 2013, 24-28 doi: 10.4236/jmmce.2013.11005.

[2.] Agunsoye, J.O., Talabi, S.I., Bello, O.: Wear characteristics of heat-treated Hadfield austenitic manganese steel for engineering application, Advances in Production Engineering& Management, 10(2), 2015, 97–107.

[3.] Aribo, S., Alaneme, K.K., Folorunso, D.O., Aramide, F.O. (). Effect of precipitation hardening on hardness and microstructure of austenitic manganese steel, Journal of Minerals and Materials Characterization and Engineer-ing, 9(2), 2010, 157-164.

[4.] Balogun, S.A., Esezobor, D.E., Agunsoye, J.O.: Effect of melting temperature on the wear characteristics of austenitic manganese steel, Journal of Minerals and Materials Characterization and Engineering, 7(3), 2008, 277-289.

[5.] Bouaziz, O., Allain, S., Scott, C.P., Cugy, P., Barbier, D.: High manganese austenitic twinning induced plas-ticity steels: A review of the microstructure properties relationships, Current Opinion in Solid State and Materials Science, 15(4), 2011, 141-168, doi: 10.1016/j.cossms.2011.04.002.

[6.] George, F. V.:ASM Handbook Metallography and Microstructures, ASM International, 9,702-703.

[7.] Olawale J. O., Ibitoye S. A., Shittu M. D.: Workhardening Behaviour and Microstructural Analysis of Failed Austenitic Manganese Steel Crusher Jaws, Materials Research., 16(6), 2013, 1274-1281

[8.] Papworth A, Williams D.B. Segregation to prior austenite grain boundaries in low alloy Steels.Scripta Mater,42, 2000, 1107-1012.
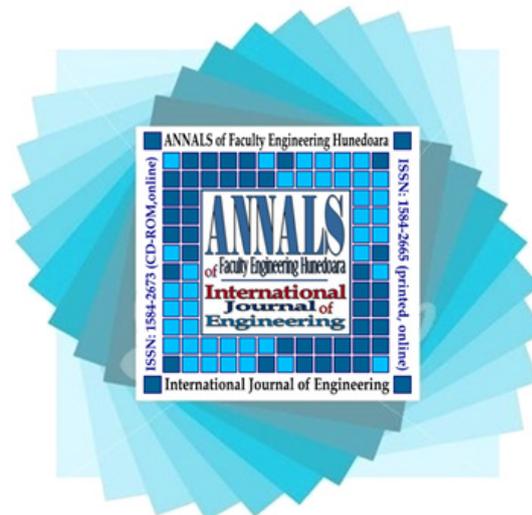
ANNALS of Faculty Engineering Hunedoara – International Journal of Engineering