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EFFECT OF ELEMENT ADDITION, MICROSTRUCTURE CHARACTERISTICS, MECHANICAL PROPERTIES, MACHINING AND WELDING PROCESSES OF THE HADFIELD AUSTENITIC MANGANESE STEEL

High manganese steel, also called Hadfield steel, is an alloy essentially made up of iron, carbon, and manganese. This type of steel occupies an important place in the industry. It possesses high impact toughness and high resistance against abrasive wear and hardens considerably during work hardening. The problem with this kind of steel is the generation of carbides at the grain boundaries after the casting. However, heat treatment at the high-temperature range between 950°C and 1150°C followed by rapid quenching in water is proposed as a solution to remove carbides and obtain a fully austenitic structure. Under the work hardening effects, the hardness of Hadfield steel increases greatly due to the transformation of the austenite γ to martensite ε or α and mechanical twinning, which acts as an obstacle for sliding dislocations. Hot machining is the only solution to machine Hadfield steel adequately without damage of tools or changing the mechanical characteristics of the steel. The choice of welding parameters is important to prevent the formation of carbides and obtain welded steel with great characteristics. This paper aims to give an overview about Hadfield steel, element addition effect, microstructure, heat treatments, work hardening, machinability and welding processes.

Keywords: Hadfield steel; austenite; carbides; element addition effect; machinability; welding

1. Introduction

Hadfield steel (1-1.4% C and 11-14% Mn), invented by Sir Robert Hadfield in 1882, is an exceptional alloy that has special mechanical characteristics [1-3]. This steel presents high characteristics such as great toughness, high strain hardening capacity and excellent abrasion wear resistance [3-5].

The presence of a high proportion of Manganese (gammagenic element) gives Hadfield steel an austenitic (FCC) structure in the as-cast state [4,6]. The alloy is soft and ductile when the structure is entirely austenitic, but under elevated loads, it hardens rapidly [7]. Only 1% of carbon gives the steel high yield strength and great tensile strength [8,9]. Besides carbon and manganese, Hadfield steel contains other elements. Indeed, in this kind of steel, we can find silicon, molybdenum and chromium…etc. The reason for varying the components or just varying their proportions is to have an alloy with high performance that responds to industrial requirements [9].

To ensure high toughness, the Hadfield steel structure must be completely austenitic; however, the moulding micro-structural analysis shows the presence of carbides in the grain boundaries and the austenite grains [10].

The precipitation of carbides at the grain boundaries promotes the propagation of microcracks, which makes the material fragile and brittle [4,8].To dissolve carbides, Hadfield steel must be heat-treated at a high temperature (up to 950°C) and rapidly quenched in water. As a result the ductility of the steel increases [8].

Hadfield steel hardens considerably on the surface and in-depth when subjected to impact loads. This hardening capacity is explained by the work hardening mechanism; a phenomenon produced by the sliding of the dislocations which induces an increase in hardness that can reach 450 HB [2,11]. Due to a particular high work hardening rate, austenitic steels can exhibit both high strength and ductility [12].

For machining high manganese steel, the cutting tool materials must be harder than the workpiece material since such characteristics require special methods “hot machining”, to achieve perfect machining [13].

In industry, certain cases require welding, for Hadfield steel, it is essential to clearly define the welding parameters (welding voltage, welding current, the heat Input, the welding speed), therefore SMAW (shielded metal arc welding) is the most widely used method, by electrodes containing a high level of Mn and Ni

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with a lower amount of carbon than the Hadfield steel to avoid the formation of the carbide [10,14,15].

For these characteristics, this alloy is used to work in aggressive industrial applications using crusher jaws, crawler tracks, mining, trails and railroad [4,5,7,16].

2. Elements addition effects

After its invention, this material was widely developed, and various new chemical elements were added to improve its mechanical and physical properties. The component elements of the standard alloy, according to ASTM A-128 are listed in TABLE 1.

TABLE 1

Composition of Hadfield steel according to standard ASTM A-128 [14,17]

Element	C	Si	Mn	P	Fe
ASTM A-128 (wt.%)	1-1.4	1 max	10-14	0.07 max	balanced

Every element has a specific effect on the manganese austenitic steel.

All steels contain Carbon with a proportion varying between 0.02-2.1% C; whereas in Hadfield steels, the proportion is usually between 0.7-1.4%. However, just 1% of C gives the steel high yield strength and high tensile strength [9]. In Manganese austenitic steel, Carbon is dissolved in the austenite to a limit of about 1.2%, above that, the carbides precipitate at the grain boundaries leading to a reduction in the ductility of the material [2]. When the Carbon content increases, the austenite grains' size and the proportion of carbides increases, while the resistance to impact and toughness decreases [18]. For ideal weldability, it is better to go with reduced carbon content in the alloy since with high carbon content there is more possibility of carbides precipitation in the affected area, thus reducing the toughness of the material [7]. At last, Carbon improves the resistance to abrasion wear, increases the yield strength and consequently the tensile strength.

Manganese is the second essential component of Hadfield steel after Carbon. This element occupies the greatest proportion in the alloy; its content varies between 10-14%. The high level of Manganese gives the alloy an austenitic structure in the raw state of elaboration [8]. Besides, Manganese serves to reduce the stacking fault energy (SFE) and increase the solubility of Carbon in interstitial positions [16]. The Manganese content does not have a significant effect on the yield strength, but it affects ductility and ultimate tensile strength (UTS), which is at maximum when the Manganese is 12 to 13% [2]. Also, Manganese increases wear resistance [11]. Indeed, the presence of this element tends to form cementite carbides $(Fe, Mn)_3C$, which are known for their great hardness that contributes to the improvement of the wear resistance of the Hadfield steel [11]. The presence of high amounts of manganese stabilzes the austenite phase and reduces the temperature of perlite and martensite transformation [15].

The combination of these two elements (Carbon and Manganese) strongly influences the mechanical properties of the material and in particular the tensile properties; the impact toughness and the wear resistance [18]. When the Carbon and Manganese content is low, the yield strength and the strain hardening coefficient increase [19]. Otherwise, a high level of Manganese and Carbon leads to a decrease in ductility and toughness [2].

Generally, the alloys based on Fe-Mn-Cr are used for corrosion-resistant [20]. However, Chromium is added to the austenitic Manganese steel to improve wear resistance and work hardening behaviour [21]. High Carbon and Chromium contents favour the formation of carbides at the grain boundaries, which produce high hardness value even before work hardening [2]. But, the excess of Manganese and Chromium carbides decrease the toughness of the material [8]. Increasing Chromium content improves hardening strength, tensile strength and reduces the friction coefficient of Manganese steels [10,22]. Several researches are based on the addition of Chromium with another component to Hadfield steel, according to S. Ayadi [23] the addition of Chromium and Niobium increases hardenability and gives additional strength to the steel due to the reduction in the grain size. C. Chen [21] reported that the addition of Chromium and Nitrogen promotes twinning behaviour during plastic deformation.

With the reduction of Carbon, the solubility of Vanadium in the austenitic matrix increases [7]. Vanadium is one of the strongest carbide forming elements in Hadfield steel [22], the level of Vanadium carbides (VC) increases with the increase in Carbon content. These carbides with a very high hardness of about 2600-3000 Hv, will generate an increase in hardness and wear resistance of the steel [5]. R.W. Smith [7] proved that the addition of 1% of Vanadium improves strength and abrasion wear resistance due to the presence of wear-resisting carbides. However; it lowers the impact strength and toughness when it exceeds 0.4% [7]. Vanadium raises significantly the yield strength but reduces the ductility [9]. K. Vdovin [24] showed that the Hadfield steel doped with Ferrovanadium Nitride amplifies the surface wear resistance in as-cast state and after heat-treatment.

Silicon is present in all types of Hadfield steel. Its concentration generally sets between 0.8-1.5% [6]. Though, it can be added up to 2% to increase the yield strength [9]. Silicon refines the martensite plates and enhances the tensile strength; however, it does not affect the ductility of the steel [25]. Silicon increases hardness due to the formation of SiC particles in the austenitic matrix [10].

Nickel is an austenite stabilizing element [9,23]. S. Ayadi [23] studied the effect of the addition of Nickel in Hadfield steel. As a result, they found that the Nickel didn't change the microstructure of the steel and contributed to the increase in wear resistance, although nickel is not a carbide-forming element. Nickel is also added to Hadfield steels to enhance ductility and improve the machinability of the steel [9].

Phosphorus must be less than 0.05% [7]. The high content of phosphorus can cause thermal tears in the casting [9] and generate the formation of phosphorus inclusions. This can be the origin of cracks propagation, which influences the impact resistance [2,7].

Other alloying elements contribute to enhance the mechanical and physical characteristics of Hadfield steel, such as; Molybdenum increases the yield strength [9], Aluminum reduces the number of carbides at grain boundaries [10], Niobium improves wear resistance and increases hardness after work hardening [16] and Cooper stabilizes the austenitic structure [9].

3. Microstructure

In the raw state after the casting, Manganese steel has an austenitic structure in which complexes carbides precipitate along with the grain boundaries and within the grains [23,26], the presence of carbides is due to the presence of the high amount of C and carbide forming elements such as Fe and Mn. The precipitation of carbides at the grain boundaries promotes the propagation of fissures and micro cracks [1,8]. In this case, the steel becomes brittle with low hardness and toughness [3,7,23]. Fig. 1 illustrates the repartition of carbides within the grain boundaries and in the austenitic matrix in the as-cast state.

When the Carbon content is higher than 1.4%, the formation of $(Fe, Mn)_3C$ carbides is increased [10]. Carbides are formed when the excess Carbon is released into the austenite during the cooling of the casting material [10]. The precipitation of carbides leads to an increase in abrasion wear resistance, but the mechanical properties such as strength and ductility drop greatly [2,10]. J.O. Olawale [11] suggested that embrittling carbides present in the moulded structure may be removed by a heat treatment process. It should also be noted that the microstructure obtained strongly depends on the casting temperature and the cooling rate of casting. Indeed, research work carried out in this context by M. Sabzi [27], varied the melting temperature during casting between 1350°C and 1450°C and noticed that when the melting temperature increases, the number of carbides and the numbers of grain boundaries decrease, however, the austenite grain size increases and the corrosion resistance also increases due to the dissolution of the carbides. Namely, when the grain size is increased the yield/ tensile strength increase, but that affects the toughness and ductility of the steel [28]. The investigation done by D. Gorlenko [29] on the influence of the cooling rate on the casting reveals that a fully austenitic structure is obtained and the martensite formation is avoided when the cooling rate exceeds 0.25°C / s, the increase in the cooling rate to an average of 1.4-16°C / s decreases the tensile and the shrinkage stresses and beyond 25°C / s generates the decrease in the austenite grain size.

4. Heat treatments

The main problem of austenitic Manganese steel is the generation of carbides in the austenite matrix and the grain boundaries after the casting of the steel [22]. Carbides influence tenacity, reduce toughness and wear resistance of the steel [1,2,7] and impair its impact strength because of the inability of the carbides to absorb chocks [11].

The objective of the heat treatment is to dissolve the carbides to produce an appropriate microstructure, without structural defects (cracks, voids, inclusions) and to obtain a homogeneous and austenitic structure without carbides [2,4].To attain this, the initial structure obtained after casting must be free from coarse inclusions, without segregation and pre-existing cracks [2]. E.G. Moghaddama [5] reported that the austenite grain boundaries are surrounded by a continuous film of fragile $(Fe, Mn)_3C$ carbides. To remove these carbides, it is necessary to heat the steel at a temperature set between 1000°C and 1100°C to dissolve the carbides, followed by quenching in water to prevent the formation of M_3C carbides again.

According to J.O. Olawale [11], the heating temperature must be quite high (about 1050°C) to dissolve the carbides formed during casting, and quenching in agitated water to increase the thermal conductivity and produce a homogeneous austenitic structure. Moreover, S.H.M. Anijdan [17] compared the quenching of an austenitized Hadfield steel at 1100°C for 2 h in pure water and salt bath (3% NaCl), the results revealed that the steel quenched in the salt bath had fewer carbides than the steel quenched in

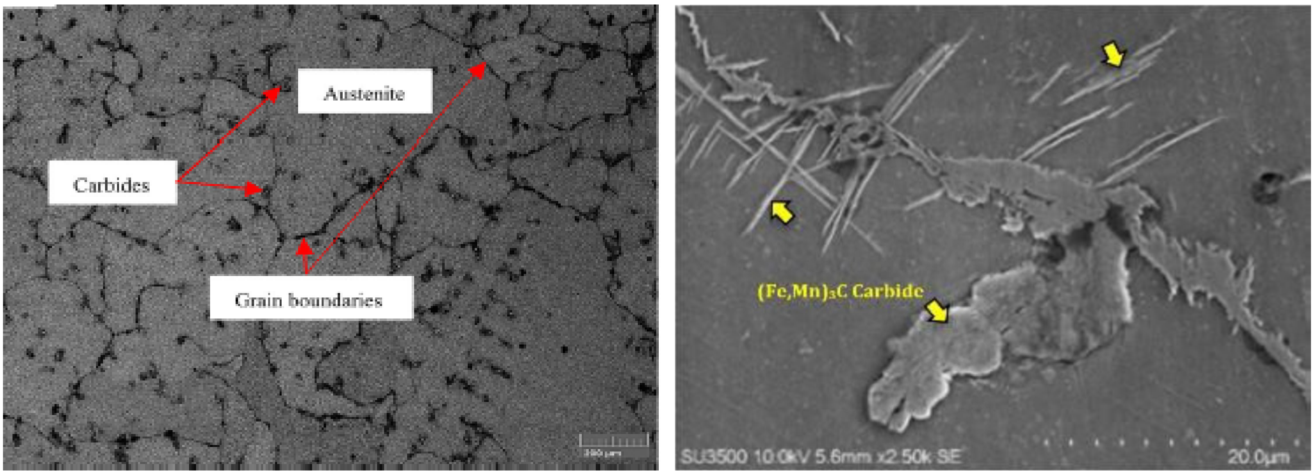

Fig. 1. SEM Micrographs showing carbides precipitation in As-cast state of high manganese steel [3,23]

pure water, besides that, quenching in a salt bath lead to higher hardness, increase toughness, ductility, and fatigue life.

For an austenitic structure free from carbides and good mechanical properties, the austenitization temperature must be perfectly controlled. H.R. Jafarian [28] reported that the increase of the austenitization the austenitization temperature from 1000°C to 1225°C, reduce the number of carbides and increase austenitic grains size, also showed a great increase in the yield/tensile strengths, hardness and good wear resistance. However, the ductility is reduced.

E.C. Reyna [1] studied the structure of Hadfield steel in the heat-affected zone after post-cooling treatments. The welded samples quenched in oil showed the existence of isolated carbides, small voids in the grains boundaries, and great massive carbides inside voids. While the welded samples cooled in the air indicate the presence of carbides of different size and microcarbides along the grain boundary [3]. Following S. Ayadi [23] increasing the temperature of the heat treatment from 1050°C to 1100°C and quenching in water promote the dissociation of secondary carbides and the formation of enriched and harder martensite. This increases the wear resistance and improves the hardness of the Hadfield steel that contains more Cr and N [21]. The Fig. 2a and 2b below show the difference in the microstructure of the Hadfield steel before and after heat treatment respectively.

5. Work hardening behaviour of the Hadfield steel

Work hardening is the crucial mechanical property of Hadfield steel. This property makes the material difficult to machine [9]. It increases considerably the hardness of Hadfield steel. This steel does not have a great hardness but under applied loads, shocks or heavy impacts, the steel hardens strongly, resulting in a wear-resistant surface [2]. The reason why Hadfield steel possesses a high hardening rate is due to several causes. Among them; are the transformation of austenite γ into martensite ε or α, dynamic strain ageing, the stacking faults interactions twin-slip and Twinning Induced Plasticity (TWIP), the formation of twins during plastic deformation as shown in Fig. 3, plays as obstacles for gliding dislocations [10,12,30]. Abrasion wear can produce deformation twinning, which leads to the formation of a hard film on the work surface [24].

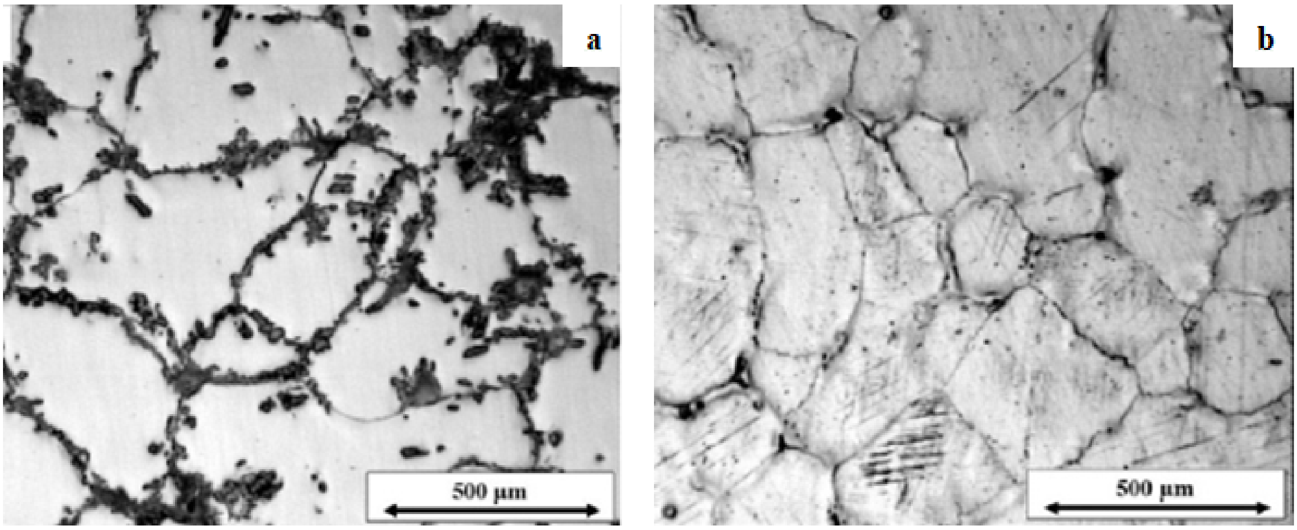

Fig. 2. Optical micrograph of the Hadfield steel: (a) before heat treatment, (b) after heat treatment [5]

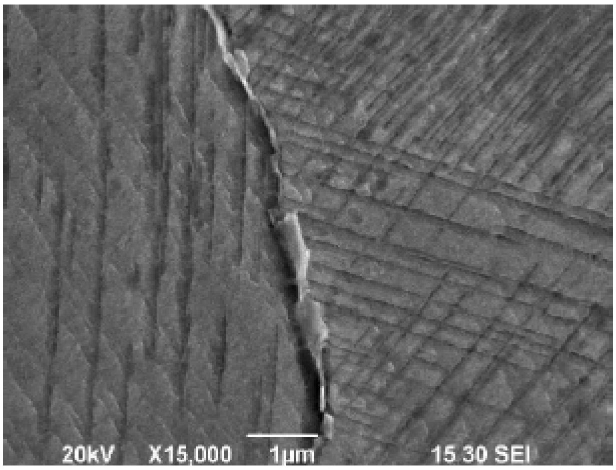

Fig. 3. Deformation twins at the austenite grain boundaries [24]

6. Machining of High Manganese Steels

Due to its particular mechanical properties such as; hardness, toughness, high wear resistance and high work hardening rate, the machinability of Hadfield steel is difficult to realize [31]. Among the constraints recognized during the machining of steel, it is the rapid wear of the cutting tool with the increase in the feed speed. the machining of the Hadfield steel induces abrasive wear on the notch of the tool which reduces its service life [32]. M. Cebron et al. [33] noted that under inappropriate machining conditions, tensile stresses may occur. This can be the origin of cracks in the surface, even though the material is not loaded yet. The work-hardening property of Hadfield steel is the main reason for the bad machinability of the material.

However, the machinability can be improved by decreasing the work hardening occurrence [9]. Hot machining has been proposed as a solution for machining Hadfield steel without the failure of tools or changing the properties of the steel [26]. The operation consists of heating the workpiece before or during machining (Fig. 4), using electric current, flame, induction heating, arc heating… etc. Increasing the temperature by more than 500°C decreases the hardness of the material and subsequently facilitates its machinability [31]. The obtained results showed that the work hardening properties decrease with the increase in the heated thickness. This technique provides an excellent surface finishing and increases the service life of the cutting tools five times more [9,26,31].

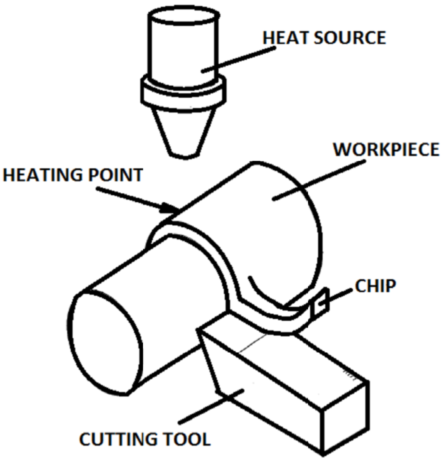

Fig. 4. Hot machining application [9]

7. The welding process of austenitic manganese steel

A lot of researche into the welding process of Hadfield steel has been done [14,15,34]. According to M. Sabzi [14], it is first of all important to determine the shape of the welded joints, because it affects the durability of the welded part. These investigators compared the effect of the shape geometry (the V and X shape) on the microstructural, mechanical and corrosive characteristics of Hadfield steel welded joints; V-shaped chamfer has higher tensile strength and hardness than X-chamfer. The latest has higher: toughness, ductility, impact energy and good corrosion resistance because it contains less carbide than the V-shaped chamfer. V. Jankauskas [34] reinforced basic Hadfield steel and Hadfield alloy steel with Cr, Ni, Mo and B by tungsten carbides, that reduced the amount of austenite in the structure and promoted good wear resistance under low applied load, but exhibits moderate wear resistance under high abrasive and erosive conditions. S.M. Dezfuli [15] studied the effect of temperature and time of the austempering process on welded hypereutectoid Hadfield steel, they found that increasing time and temperature resulted in a decrease in austenite grain size and ductility. Following their study, heat treatment of the welding joints at 600°C during 30 min provided the optimal result of microstructure, mechanical properties and fracture mode.

8. Conclusion

This paper aimed to provide generalities about austenitic Manganese steel known as Hadfield steel.

1. The standard Hadfield steel alloy contains 1-1.4% Carbon and 11-14% Manganese, characterized by a high tenacity, high tensile strength and good abrasion wear resistance.
2. The optimum structure of Hadfield steel is fully austenitic (FCC). However, after casting, microscopy revealed the presence of complex carbides precipitated at the grain boundaries and in the austenitic matrix. These carbides reduce toughness; ductility and the ability of the material to absorb shocks which make the material fragile and brittle.
3. Carbides must be eliminated by the heat treatment process. Quenching the steel after austenitization at a high temperature (950-1150°C) in an agitated salt bath lead to reduce or remove carbides, higher the hardness, increase toughness, ductility and fatigue life.
4. The hardness of Hadfield steel is not high sufficiently. However, the formation of twins during plastic deformation and accumulation of dislocations by work hardening contribute to increasing its hardness greatly.
5. Hot machining is the main desirable process to machine Hadfield steel without changing its characteristics and conserves tools from early damage.
6. SMAW (Shielded Metal Arc Welding) is the most widely used method for welding Hadfield steel, where it is important to specify the shape of the welded joint and to apply a heat treatment (austempering) with the appropriate parameters to avoid the deposition of carbides and optimize the yield of welded steel.

REFERENCES

[1] E. Curiel-Reyna, J. Contreras, T. Rangel-Ortis, A. Herrera, L. Baños, A. del. Real, M.E. Rodríguez, Mater. Manuf. Process. **23** (1), 14-20 (2008).

[2] S.W. Bhero, B. Nyembe, K. Lentsoana, CMMME' 2013. 174-175 (2013).

[3] B. Bandanadjaja, E. Hidayat, J. Phys.: Conf. Ser. 1450, 012125 (2020).

[4] A. Hajjaji, B. Boubeker, A. Zamma, S. Eljoumani, M. Idiri, H. Essaghir, 12ème Congrès de Mécanique, (2015).

[5] E.G. Moghaddam, N. Varahram, P. Davami, Mater. Sci. Eng. A. **532**, 260-266 (2012)

[6] A. Šalak, M. Selecká, Manganese in powder metallurgy steels, Springer Science & Business Media, (2012).

[7] R.W. Smith, W.B.F. Mackay, Can. Metall. Quart. **42** (3), 333-342 (2003).

[8] S.E. Madani, O.B. Lenda, F. Sabir, S. Elhamzi, H. Gziri, A. Ibnlfassi, L. Zerrouk, J. Adv. Phy. **10** (2), 2762-2773 (2015).

[9] O. Çakir, ICAME 2016, 227-232 (2016).

[10] M. Sabzi, M. Farzam, Mater. Res. Express. **6** (10), 1065c2 (2019)

[11] J.O. Olawale, S.A. Ibitoye, M.D. Shittu, Mater. Res. **16** (6), 1274-1281 (2013)

[12] O. Bouaziz, N. Guelton, Mater. Sci. Eng. A. **319**, 246-249 (2001)

[13] N. Tosun, L. Ozler, Int. J. Adv. Manuf. Technol. **23** (11-12), 777–782 (2004)

[14] M. Sabzi, A. Obeydavi, S.H. Mousavi Anijdan, Mech. Adv. Mater. Struct. **26** (12), 1053-1063 (2019).

[15] M. Sabzi, S.M. Dezfuli, J. Manuf. Process. **34** (April), 313-328 (2018).

[16] A. Hadji, H. Maouche, K. Bouhamla, CPI2011 (2011).

[17] S.H. Mousavi Anijdan, M. Sabzi, J. Mater. Eng. Perform. **27** (10), 5246-5253 (2018).

[18] U. Gürol, S.C Kurnaz, J. Min. Metall. Sect. B. **56** (2), 171-182 (2020).

[19] N. Popova, T. Dement, E. Nikonenko, I. Kurzina, E. Kozlov, AIP Conference Proceedings, (2017).

[20] R. Fadhila, A.G. Jaharah, M.Z. Omar, C.H.C. Haron, M.J. Ghazali, A. Manaf, C.H. Azhari, Int. J. Mech. Mater. Eng. **2** (2), 150-153 (2007).

[21] C. Chen, B. Lv, H. Ma, D. Sun, F. Zhang, Tribol. Int. **121**, 389-399 (2018).

[22] O.E. Falodun, S.R. Oke, A.M. Okoro, P.A. Olubambi, Mater. Today-Pro. **28**, 730-733 (2020).

[23] S. Ayadi, A. Hadji, Inter Metalcast (2020). DOI: https://doi.org/10.1007/s40962-020-00479-2 (in press).

[24] K. Vdovin, A. Pesin, N. Feoktistov, D. Gorlenko, Metal. **8** (10), 845 (2018).

[25] J. Safarian, L. Kolbeinsen, In 13th International Ferro-Alloys Congress, Almaty, Kazakhstan, 175-183 (2013).

[26] C. Okechukwu, A.D. Olurotimi, K.O. Peter, O.O. Isiaka, D. Mohammed, Int. J. Eng. Tech. **3** (2), 83-90 (2017).

[27] M. Sabzi, S.M. Far, S.M. Dezfuli, Int. J. Miner. Metall. Mater. **25** (12), 1431-1438 (2018).

[28] H.R. Jafarian, M. Sabzi, S.H.M. Anijdan, A.R. Eivani, N. Park, J. Mater. Res. Technol. **10**, 819-831 (2020).

[29] D. Gorlenko, K. Vdovin, N. Feoktistov, China Foundry **6**, 433-442 (2016).

[30] O.A. Zambrano, G. Tressia, R.M. Souza, Eng. Fail. Anal. **115**, 104621 (2020).

[31] O. Çakır, E. Altan, Trends in the development of machinery and associated technology, 105-108 (2008).

[32] E. Kuljanic, M. Sortino, G. Totis, F. Prosperi, Scientific Proceedings Ix International Congress "Machines, Technologies, Materials" **1**, 131-134 (2012).

[33] J. Kopac, M. Cebron, F. Kosel, J. Ach. Mate. Manuf. Eng. **55** (1), 80-89 (2012).

[34] V. Jankauskas, R. Choteborsky, M. Antonov, E. Katinas, **39** (1), 78-84 (2018).