Mechanical properties and corrosion resistance of grinding ball Fe-xMn-10Al-1.25C alloys

R Kartikasari¹, *, A E Wijaya¹, A D Iskandar¹, S Subardi¹ and T Triyono²

¹Mechanical Engineering Department, “Nasional” College of Technology (Sekolah Tinggi Teknologi Nasional) Jl. Babarsari No.1 Caturtunggal, Depok, Sleman, Yogyakarta, Indonesia 55281
²Mechanical Engineering Department, Universitas Sebelas Maret, Surakarta, Indonesia

*ratna@sttnas.ac.id

Abstract. This research aims to determine mechanical properties of grinding ball Fe-xMn-10Al-1.25C alloys. The grinding ball alloys were prepared by an induction furnace under argon atmosphere. Al and C levels, 10% and 1.25% respectively, in Fe-Al-Mn grinding ball were kept constant while Mn content was varied by 15%, 20% and 25%. Grinding ball of Fe-Cr-C alloy as a comparison was obtained from the cement industry. Mechanical properties were investigated using tensile testing machine, Vickers hardness testing machine, Charpy impact test machine, and wear testing machine. Corrosion resistance was investigated using weight loss method. The results showed that the best mechanical properties occurred at 25% Mn composition, which were superior to Fe-Cr-C grinding ball. The ultimate tensile strength (UTS), yield strength, and elongation of Fe-xMn-10Al-1.25C grinding balls were in the range of 1215-1435 MPa, 927-1135 MPa, and 40.74-57.72% respectively. The hardness of these alloys was in the range of 421-550 VHN, the Charpy impact of these alloys was in the range of 1.24-1.55 J/mm², while wear resistance of these alloys was in the range of 0.0004-0.0007 gr/s. The mechanical properties of Fe-Cr-C grinding ball were 1125 MPa (tensile strength), 875 MPa (yield strength), 47.8% (elongation), 544 VHN, 0.45J/mm² (toughness), and 0.0004 gr/s (wear resistance) respectively. The best corrosion resistance of Fe-5Al-xMn-1.25C and Fe-Cr-C grinding balls were 0.016 mm/yr and 0.035 mm/yr respectively.

1. Introduction
Grinding balls which have been used in ball mills are common grinding equipment in mineral processing and cement industries [1,2]. Ball wear is resulted from three mechanisms namely impact, abrasion, and corrosion. Because of its chemical-electrochemical properties, the corrosion mechanism is the least explored [1]. In order to obtain the best performance, which are the lowest wear rate and highest grinding transfer to cost ratio, ball producers resort to various fabricating methods base on properties, size, and chemical composition of the products. The fabricating methods used are cold and hot die forging, roll and skew roll forging, and die and sand casting. The selection of fabricating process is determined by milling environments since different environment require different properties [3].

Most of grinding balls are made of high chromium white cast irons considering their great potential as wear resistant materials in mineral processing and other applications [3]. Wear is one of the important cost factors during mineral processing [4-9]. Various studies have reported that grinding balls are made
of Cr alloy [10] which have excellent properties because of Cr content [11]. Unfortunately, the presence of Cr as a major alloying element in Fe-Cr alloys is limited to southern Africa and Zimbabwe, so the cost of producing these alloys is expensive [12-14]. Therefore, the world researchers are looking for an alternative new alloy to replace Fe-Cr alloy.

For few decades, Fe-Al-Mn Alloys have got a lot of researchers’ attention as a substitute for some of the conventional Fe-Ni-Cr stainless steels. These alloys show great characters, especially corrosion and high temperature oxidation resistance [15-19]. Because of economic and strategic reason, Al and Mn are used to substitute Cr and Ni used in conventional steel [20].

As reported previously, several isothermal sections for Fe-Al-Mn are ternary alloy [20], s. Fe-Al-Mn alloys are composed of ferrite and austenite phases. Some of them are single phase (either ferrite or austenite), and the others are dual phase (duplex). It is well known that Mn and Al are austenite and ferrite formers, respectively. Higher Mn content causes a higher proportion of the austenite phase to emerge at low temperatures in contrast to the full ferrite phase in plain carbon steels [17].

The present work attempts to investigate the effect of Mn on mechanical properties, namely tensile strength, impact toughness, hardness, wear rate, and corrosion resistance of Fe-xMn-10Al-1.25C alloys for grinding ball application.

2. Experimental procedure
Fifty kilograms of Fe-xMn-10Al-1.25C alloy was prepared from mild steel scrap, high purity aluminium, Fe-Mn medium C, and Fe-C. These alloys were prepared in an induction furnace under argon atmosphere. The chemical compositions are listed in table 1. The ingot was cut using bimetallic band saw blade to make specimens for microstructure (14 mm in gauge diameter and 10 mm in gauge length) and corrosion (14 mm in gauge diameter and 3mm in gauge length) studies. The microstructure specimens were examined using optical and electron microscope. The phases present in the specimens were identified using X-ray diffraction technique. A copper target with nickel filter and graphite single crystal monochromater was used to record the diffraction pattern. The Vickers hardness specimens were made on longitudinal sections. The Impact Charpy specimens of 3 mm x 10 mm x 55 mm with 2 mm v-notch were based on JIS Z 2242 standard. Corrosion specimens were made based on ASTM G 30 (14 mm in gauge diameter and 3 mm in gauge length). The surface of the corrosion specimens was mechanically polished with abrasive paper up to 1200 grit after surface finishing. The last mechanical polishing was done with 0.5 µm alumina paste. The corrosion measurements were carried out with weight loss method. The corrosion type and the morphology of the oxide scale were determined by optical and scanning electron microscope (SEM). Corrosions products were examined using EDS/EDAX. The polished section was subsequently etched with 3.3% HNO3-3.3% CH3COOH-0.1% HF-93.3% H2O by volume for micro structural examination by optical microscope.

3. Results and discussion
The chemical compositions of the three alloys grinding ball are shown in table 1. Chemical composition test of Fe-Al-Mn grinding ball alloy was carried out using spectrometry method which consisted of three compositions. The chemical analyses indicate that the grinding ball of alloy 1, alloy 2 and alloy 3 are Fe-Al-Mn-C high alloy steel. The elements in Fe-Al-Mn-C high alloy steel are Carbon, Aluminium, Manganese (Mn), Silicon, Phosphorus and Sulphur.

The overall results of the chemical composition test indicate that the composition of the grinding ball is in accordance with the target set. Figure 1 and 2 show the results of the interpretation of the XRD curve. This interpretation shows that the phases of Fe-Al-Mn-C grinding ball are austenite and ferrite. This phenomenon is caused by the presence of Mn as an austenite stabilizer and Al as a ferrite structure stabilizer. The Mn element can increase the strength and corrosion resistance of Fe-Al-Mn-C alloys. The percentage of the added alloy will affect the microstructure and grain size, which also determines the mechanical properties of the alloys.

Figure 1 and 2 show the results of the interpretation of the XRD curve. This interpretation shows that the phases of Fe-Al-Mn-C grinding ball are austenite and ferrite. This phenomenon is caused by the
presence of Mn as an austenite stabilizer and Al as a ferrite structure stabilizer. The Mn element can increase the strength and corrosion resistance of Fe-Al-Mn-C alloys. The percentage of the added alloy will affect the microstructure and grain size, which also determines the mechanical properties of the alloys.

**Table 1.** Chemical Composition of Fe-Al-Mn alloy.

| Element | Alloy 1 | Alloy 2 | Alloy 3 |
|---------|---------|---------|---------|
| Fe      | 52.6    | 57.     | 67.77   |
| C       | 1.25    | 1.02    | 1.01    |
| Al      | 10.01   | 10.03   | 10.02   |
| Mn      | 15.05   | 20.01   | 25.1    |
| Si      | 1.05    | 1.05    | 1.05    |
| P       | 0.03    | 0.03    | 0.03    |
| S       | 0.02    | 0.02    | 0.02    |

**Figure 1.** The diffraction pattern of Fe-15Mn 10Al-1.25C Grinding ball (alloy 1).

### 3.1. Mechanical properties

#### 3.1.1. Tensile strength

The tensile strength of Fe-Al-Mn-C grinding ball is in the range of 1215 - 1435 MPa, where the higher its Mn content, the higher its tensile strength is (figure 2). The yield strengths of Fe-Al-Mn alloy range from 927 to 1135 MPa, while the strain is in the range of 40.74 to 50.72%. Figure 2 shows that the tensile strength of Fe-Al-Mn-C grinding ball at 25wt% Mn content exceeds the tensile strength of Fe-Cr grinding ball. This shows that Fe-Al-Mn-C alloy can be nominated to replace Fe-Cr grinding ball.

The broken surfaces of the specimen after the tensile test show the brittle and ductile mixture fracture pattern, meaning that the Fe-Al-Mn grinding ball alloy has a fairly high toughness. It was proven that the higher Mn content of this alloy, the higher its tensile strength and yield strength are [18]. Besides, the structure of austenite which is stable at room temperature increases when the Mn level increases [19].
Grinding ball of Fe-Al-Mn alloy with 15 wt% Mn has a strain of 40.74%. The next two compositions, namely 20 Mn and 25 Mn, have greater strain of 50.4 wt%, and 57.72% (figure 2). Higher strain on higher Mn levels is caused by lower lattice density at higher Mn level because Mn atoms that occupy the position of Fe atoms have larger size than Fe atoms. The increase in strength accompanied by an increase in strain is an advantage of the Fe-Al-Mn-C alloy. This phenomenon is caused by the combination effect of the presence of Al, Mn and C elements in the alloy system. The formation of Fe-Al-Mn-C solid solution causes an increase in strength and strain at the same time significantly.

3.1.2. Hardness. The Vickers hardness of Fe-Al-Mn-C grinding ball is in the range of 421-544 VHN (figure 3). Increase of Mn levels in Fe-Al-Mn-C alloy causes an increase in the value of hardness. An increase in Mn levels from 15% to 20% caused an increase in the hardness value of 10.5% while an increase in Mn levels up to 25% causes an increase in the value of hardness up to 30.64%.

The highest hardness value occurs at 25% Mn level namely 550 VHN. When Mn level increases the changes in microstructure occur: ferrite structure decrease while the amount of austenite structure increase. This led to an increase in the value of hardness. The increase in the value of hardness is equivalent to the increase in tensile strength due to the increase of Mn levels. Mn atoms which occupy the position of Fe atoms shift Al atoms in the Fe-Al-Mn alloy system and cause an increase in lattice density so that the hardness increases [21]. Because the size of the Mn atom (1.79 Angstrom) is much smaller than the size of the Al atom (1.82 Angstroms) and closer to the size of the Fe atom (1.72 Angstrom), the increase in hardness is quite significant.

3.1.3. Impact properties. The results of the impact test of the Fe-Al-Mn ball grinding are shown in figure 4. The toughness of grinding ball of Fe-Al-Mn alloy at 15% Mn level is 1.29 J/mm2. It increases when Mn content increases [22]. A 20% Mn level increases toughness by 10.1%, while an increase in Mn levels up to 25% increases toughness up to 21.7%. The addition of Mn to the Fe-Al-Mn alloy results in a significant increase in toughness.
The increase in strength followed by a significant increase in ductility resulted in a very high increase in toughness. This is caused by changes in the microstructure of the alloy towards austenitic. This phenomenon is clearly seen on the broken surface of the impact specimens of Fe-Al-Mn grinding ball (figure 5), where ductile fracture patterns are seen in all three Mn levels. Broken surfaces indicate the presence of necking on three compositions of Mn where necking is greater with higher levels of Mn. Mn substitution in the Fe system is a significant cause of the increase in toughness. The difference between the atomic distances (lattice) causes the movement of atoms in the material when it receives loads more freely. Mechanically, the value of toughness, ductility and strain is higher.

3.1.4. Wear properties. Figure 6 shows the wear rate of Fe-Al-Mn-C grinding ball. The highest wear rate occurs at the lowest Mn level of 15% Mn. The higher the Mn level, the lower the wear value is. Increased Mn levels reduce the level of wear up to 28.6% at 20% Mn levels and 42.9% at 25% Mn levels. This phenomenon is similar to hardness properties. Viewed from its atom arrangement, Mn atoms occupying the position of Fe atoms shift Al atoms in the Fe-Al-Mn-C alloy system. This causes the increases of lattice density so the wear resistance increases.

3.2. Corrosion resistance
Grinding ball of Fe-Al-Mn alloy has a corrosion rate in the range of 0.036-0.042 mm/year in 0.5% NaCl media, which tends to decrease Mn content in the alloy is higher (Figure 7). In addition to the role of increasing strength and toughness, Mn element in Fe-Al-Mn-C alloys, also plays a role in stabilizing the austenite structure at room temperature and increasing the corrosion resistance of alloys. The corrosion rate of Fe-Al-Mn-C alloy up to 25% Mn belongs to a very good category. The increased of Mn levels increase corrosion resistance up to 14.2%. There are corrosion products from elements of Fe, Al and Mn in the form of oxides. The overall results of this research show that all Fe-Al-Mn-C alloy composition can be used to replace Fe-Cr grinding ball.
Figure 6. Wear rate of Fe-Al-Mn-C grinding ball. Figure 7. Corrosion rate of Fe-Al-Mn-C grinding ball.

4. Conclusion
It was proven that all Fe-Al-Mn-C alloys are suitable for replacing Fe-Cr grinding ball. The best candidate for replacing Fe-Cr grinding ball is Fe-Al-Mn-C alloy with 25% Mn content.

Acknowledgment
The authors would like to thank Ministry of Research, Technology and Higher Education of Indonesia for financially supporting this research by “Hibah Penelitian Strategis Nasional Institusi” (Decree No: 3/E/KPT/2018).

References
[1] Asghar A, Seid Z S, Mohammad N and Mohammad K 2015 An investigation of the corrosive wear of steel balls in grinding of Ores IJMGE Int. J. Min. & Geo-Eng 49(1) 83-91
[2] Vermeulen L A and Howat D D 1986 Abrasive and impactive wear of grinding balls in rotary mills J. South African Institute of Mining and Metallurgy 86(4) 113-24
[3] Jankovic A, Wills T and Dikmen S 2016 A comparison of wear rates of ball mill grinding media Journal of Mining and Metallurgy A: Mining 52(1) 1-10
[4] Norman T E 1980 Wear in ore processing machinery. In: Wear Control Handbook (ASME, Peterson M B, Winor W O eds) p 109-151
[5] Nass D E 1974 Steel grinding media used in the United States and Canada In: Symposium Materials For The Mining Industry. Vail, Co., E.U.A. p 173-83
[6] Vermeulen L A and Howat D D 1983 Theories of ball wear and the results of a markedball test in ball milling J. South African Institute of Mining and Metallurgy 83(8) p 189-97
[7] Barros L A 1991 Testes de avaliação de corpos moedores (Grinding media evaluation tests). In: Seminário Sobre Materiais Resistentes Ao Desgaste, 2., (2nd Wear Resistant Materials Seminar) (Uberlândia, MG, Brazil: ABM and Universidade Federal de Uberlândia, Uberlândia M G) p 570
[8] Durman R W 1988 Progress in abrasion resistant materials for use in comminution processes Int. Journal of Mineral Processing p 381-99
[9] Durman R W 1972 The application of alloyed white cast irons in crushing, grinding and material handling processes The British Foundryman p 381-99
[10] Maldonado-Ruiz S I, Orozco-González P, Baltazar-Hernández V H, Bedolla-Jacuinde A and Hernández-Rodriguez M A L 2014 Effect of V-Ti on the Microstructure and Abrasive Wear Behavior of 6CrC Cast Steel Mill Balls Journal of Minerals and Materials Characterization and Engineering 2 383-391
[11] Tjong S C 1986 Stress Corrosion Cracking behavior of the duplex Fe-10Al-29Mn-0.4C alloy in 20% NaCl solution at 100oC Journal of Material Science 21 p 1166-1170
[12] Kao C H and Wan C M 1987 Effect of Carbon on the Oxidation of Fe-5.5Al-0.55C Alloy. *Journal of Materials Science* **22** 3203-3208
[13] Kao C H and Wan C M 1988 Effect of Manganese on the oxidation of Fe-Mn-Al-C Alloys. *Journal of Materials Science* **23** 744-752
[14] Wang S, Zhang H and Chen S J 2000 Experiment on Fe-Al-Mn Deoxidizing and Alloying of Low-carbon Aluminum Killed Steel. *Journal Iron Steel Vanadium Titanium* **21**(4) 44-49
[15] Jackson P R S and Wallwork G R 1984 High temperature oxidation of iron-manganese-aluminum based alloys. *Oxidation of metals* **21**(3-4) 135-170
[16] Duh J G and Wang C J 1990 Formation and growth morphology of oxidation-induced ferrite layer in Fe-Mn-Al-Cr-C alloys. *Journal of Materials Science* **25**(4) 2063-2070
[17] Wei-Chun C, Chia-Fu L and Yi-Fan L 2002 Observing the D03 phase in Fe-/Mn-Al alloys. *Materials Science and Engineering*. A337 281-286
[18] Kartikasari R 2015 Effect of Mangan Content on Mechanical Properties and Corrosion Behavior of as Cast Fe-7.5Al-0.6C Alloy. *International Journal of Applied Engineering Research* **10**(13)
[19] Kartikasari R 2014 Effect of Aluminum Content on Microstructure and Corrosion Behavior of as Cast Fe-Al-C Alloys. *Lightweight Steel International Journal of Applied Engineering Research* **9**(13) 2241-2249
[20] Liu X J, Hao S M, Xu L Y, Guo Y F and Chen H 1996 Experimental study of the phase equilibria in the Fe-Mn-Al system. *Metallurgical and Materials Transactions A* **27**(9) 2429-2435
[21] Zuazo I and Brechet Y 2009 Microstructure Evolution in Fe-Al-Mn-C lightweight alloys, *Laboratory of Science and Engineering of Materials and Processes (SIMaP) (Grenoble Institute of Technology (INGP))*
[22] Baligidad R G, Satya P V V and Sambasiva R A 2007 Effect of Ti, W, Mn, Mo, and Si on Microstructure and Mechanical Properties of High Carbon Fe-10,5wt% Al Alloy. *Journal of Material Science and Technology* **23**(5) 613-619