International Journal of Applied Engineering Research
ISSN 0973-4562 Volume 9, Number 13 (2014) pp. 2241-2249
© Research India Publications
https://dx.doi.org/10.37622/IJAER/9.13.2014.2241-2249

Effect of Aluminum Content on Microstructure and Corrosion Behavior of as Cast Fe-Al-C Alloys Lightweight Steel

Ratna Kartikasari

Department of Mechanical Engineering,
"Nasional" College of Technology, Jl. Babarsari No. 1,
CT, Yogyakarta, Indonesia 55281

Abstract

Effects of aluminum content on microstructure and corrosion behavior of as cast Fe-Al-C alloys lightweight steel have been studied. The alloys were prepared by an induction furnace under an argon atmosphere. Microstructure of Fe-Al-C alloys containing 1.24, 3.3, 5.5, 7.5, and 9.05 wt-% aluminum showed ferrite and pearlite, where the higher levels of Al increases the amount of ferrite structures. Scanning electron microscope test results indicate the presence of aluminum carbides at the grain boundary of pearlite of Fe-Al-C alloy with 3.3% up to 9.05% Al. At 9.05% Al alloy structure nearly 100% ferrite, pearlite structures remaining are in the ferrite grain boundaries. An increase Al content resulted in significant improvement corrosion resistance in 0.5% NaCl solution.

Keyword: Fe-Al-C alloys, argon atmosphere, microstructure, corrosion resistance

Introduction

The steel is still ranked as the top (90%) material in the world until now [1]. The impact of the world energy crisis demands technological innovation on all fronts for the discovery of new energy sources and efficient use of energy. In the field of materials, innovation focused on the invention of development of materials that support of energy savings. Development of lightweight Steel is the research focus of the world steel practitioners. An experiment of steel alloyed with light metals is one of the efforts to achieve the target of lowering the density of steel.

Adding a large amount of light elements such as aluminum to steels is not a new concept recalling that several Fe-Al-Mn-C alloys were patented in 1950s for replacement of nickel or chromium in corrosion resistance steels. However, the so-called lightweight steels or low-density steels were revisited recently, which is driven by demands from the industry where steel has served as a major structural material. Strengthening without loss of ductility has been a triumph in steel research, but lowering the density of steel by mixing with light elements will be another prospect that may support the competitiveness against emerging alternatives such as magnesium alloys. In this paper, we review recent studies on lightweight steels, emphasizing the concept of alloy design for microstructures and mechanical properties [2].

Newly developed lightweight steel based on ferritic iron aluminum or austenitic-manganese aluminum are showing promising physical, mechanical, and technological properties, such as high specific elastic stiffness and strength, excellent ductility and formability, reduced specific weight, and an improved corrosion resistance as well[3].

It has been developed that Fe-Al-C alloy is a good candidate for replacing some of the conventional stainless steel in several applications at moderate to high temperature [4]. Wherein, Al is used to substitute expensive alloy elements in conventional Fe-Cr-C system. Ferritic iron aluminum alloys shows promising physical and mechanical properties along with superior corrosion and oxidation resistance at much lower raw material cost [5]. Therefore it is suitable for development of new type of high strength lightweight steel [3]. Besides these the plain iron-aluminum steel containing up to 9 wt-% Al has substantially lower density of at least 10%.

Fe-Al alloys exhibit poor toughness. These are brittle at room temperature [6]. Addition of carbon to Fe-Al containing 8.5 to 16 wt-% Al gives higher strength [7], and better machinability [8]. It has been shown that low carbon content (0.5 and 0.1 wt-%) in Fe-9 wt-% Al leads *to* low tensile ductility. Whereas, the ESR (Electro Slag Refined) ingots of Fe-10.5Al and Fe-13Al alloys containing high (0.5 and 1.0 wt-%) carbon exhibit excellent hot workability [9]. Fe-Al-C alloy is being developed for elevated temperature structural application up to 873K [10].

Aluminum plays a major role in the oxidation and corrosion resistance which is characteristic of the binary Fe-Al alloy [11]. The Fe-Al-C alloys have good corrosion resistance in a neutral environment. Its corrosion rates are comparable to that of white cast-iron in acid environments [12]. However, few data are available on the corrosion phenomena of Fe-Al alloy in low concentration acid media. The aims of this research are to evaluate the effect of aluminum content on microstructure and corrosion behavior of as cast Fe-Al-C alloys lightweight steel.

Experiment Procedure

Thirty five kilograms of Fe-Al-C was prepared from mild steel scrap, high purity aluminum, and Fe-C. The alloy was 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 3 mm in gauge length) studies. The microstructure specimens were examined by optical and electron microscope. The phases present in the specimens were identified *by*X-ray diffraction technique. A copper target with nickel filter and graphite single crystal monochrometer was used to record the diffraction pattern.

The surface of the corrosion specimens were 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 three-electrode polarization in 0.5% NaCl. 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 were subsequently etched with 3.3% HNO3-3.3% CH3COOH-0.1% HF-93.3% H2O by volume for micro structural examination by optical microscope.

Result and Discussion

Microstructure

Figure 1 shows the optical microstructures of the cast alloys. The as cast alloys are composed of ferrite and pearlite at all level Al, where higher level of Al increases the amount of ferrite phases but decreases the amount of pearlite phases. At the Al content of 9.05% is a low pearlite phases remains only in the area along the grain boundaries. This proved the role of Al as a ferrite stabilizer in the Fe-Al-C alloy so that the higher levels of Al will be the more ferrite structures are formed. Based on the phase diagram of Fe-Al [13] up to 10 wt-% Al content the stable phase is ferrite. The presence of carbon a fairly high (0.6 wt-%) led to appearance pearlite phase is quite dominated, especially at levels up to 7.5% Al. The Al atoms (atomic radius of 1.82 A), in the system of Fe will take a position as a solid solution substitution, due to atomic radius of Al is greater than the atomic radius of Fe- Al phase diagram [3]. On the iron rich side, three types of b.c.c lattice structures are present. These are the non ordered A2 lattice which occurs in the iron-aluminum solid solution up to about 20 at-% Al (10 wt-% Al) at room and high temperatures. Here the iron and aluminum atoms are statistically distribute in the lattice.

Figure 1a shows presence of ferrite and pearlite grains are tend to form equiaxed. As seen figure 1b, c, d and e, dendrite structure more clearly looked; this is due the nucleation of Al carbide which has dendritic pattern [14]. The higher levels of Al dendrite structure decreases and dominated by the ferrite structure. Up to Al content 9.05% ferrite crystal structure has not been reached perfect. Fe-Al alloy-C will be have the perfect ferrite structure at content Al 12%, the phase will be a 100% alloy ferritic on Al content above 10% [9].

Figure 2 shows SEM images of the Fe-Al-C alloy FeAl is seen that the precipitate is white and uniformly distributed. This precipitate has a BCC atoms structure [9]. Intermetallic compounds of FeAl have the BCC structure (A2) to Al content 10 wt-10% [3]. The higher levels of Al tendency FeAl intermetallic greater preparation into lamellar with arrangement according to certain patterns. The higher level of Al lamellar FeAlis looks increasingly thick and wide. SEM test result indicate the presence of aluminum carbides at the grain boundaries of pearlite of Fe-Al-C alloy with 3.3% up to 9.05% Al. Interpretation of the results of XRD curves (figur 3) show that there is a ferrite phase.

Corrosion Behavior

Corrosion testing performed using the technique of polarization in 0.5% NaCl solution. Corrosion test result shown in figure 4 and 5. Quantitative value of the metal corroded corrosion rate calculated by the formula as in(1), the unit used is mm / year.

$$R = 0,\,129\frac{(I_{corr}).EW}{\rho}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (1)$$

Where:

R = corrosion rate (mpy)
I_{corr} = current density (µA/cm^2)
ρ = density (gr/cm^3)
EW = equivalent weight (gr/equivalent)
EW = 1/N_{EQ}
N_{EQ} = $\sum[\frac{N_i f_i}{a_i}]$
n_i = valence
f_i = weight fraction
a_i = atomic weight

Corrosion rate of Fe-Al-C Alloy in 0.5% NaCl media ranged from 0.091 to 0.147 mm / year (table 2).Highest corrosion rate at a level is equal to lowest Al 0.147 mm / year. Based on the level of corrosion resistance table Fe-Al-C alloy with Al content of 1.2 and 3.3% had a corrosion rate of 0.147 and 0.104 mm / year are included in a good category. In the range of 5.05% - 9.09% Al corrosion rate Fe-Al-C alloy by 0.091 to 0.084 mm / year included in the category very good. At higher levels of Al corrosion rate decreased and reached the lowest value in the Al content of 7.5% is equal to 0.084, increased levels of Al furthermore does cause an increase in the rate of corrosion.

Excellent corrosion resistance of the alloy Fe-Al-C is due to the presence of elements of aluminum in the alloy system. Aluminum elements would form a layer of aluminum oxide. Thin film of aluminum oxide (Al_2O_3) is formed on the surface due to contact with the alloy containing oxygen environment capable of providing protection against further corrosion process. At a temperature 600ºC in addition found also found the compound Al_2O_3 (FeAl(1-x)) 2O3 on the oxidized surface. The corrosion of Fe-16Al-0, 05C alloy at higher temperatures would be lower due to decrease in number of phase Fe_3AlC [15]. The ferrite phase FeAl also contributed to the corrosion of Fe-Al-C alloy [16]. So Fe_3AlC carbide formation and FeAl ferrite phase in the alloy system is able to improve the corrosion resistance of the alloy significantly.

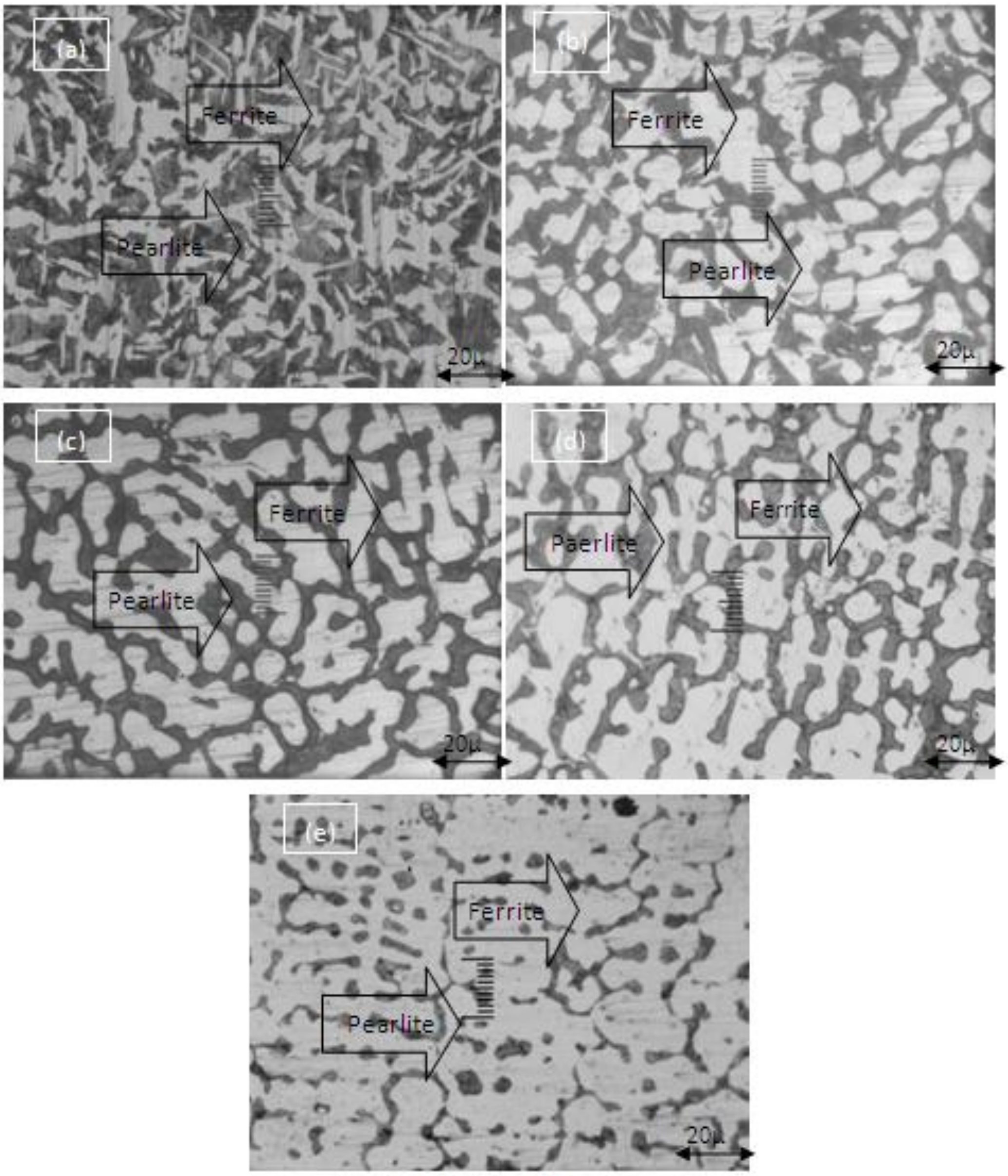

Fig. 1. Microstructure of as cast alloys Fe-Al-C. (a). Fe-1,24Al (b). Fe-3,3Al (c). Fe-5,5Al (d). Fe-7,5Al (e). Fe-9,05Al

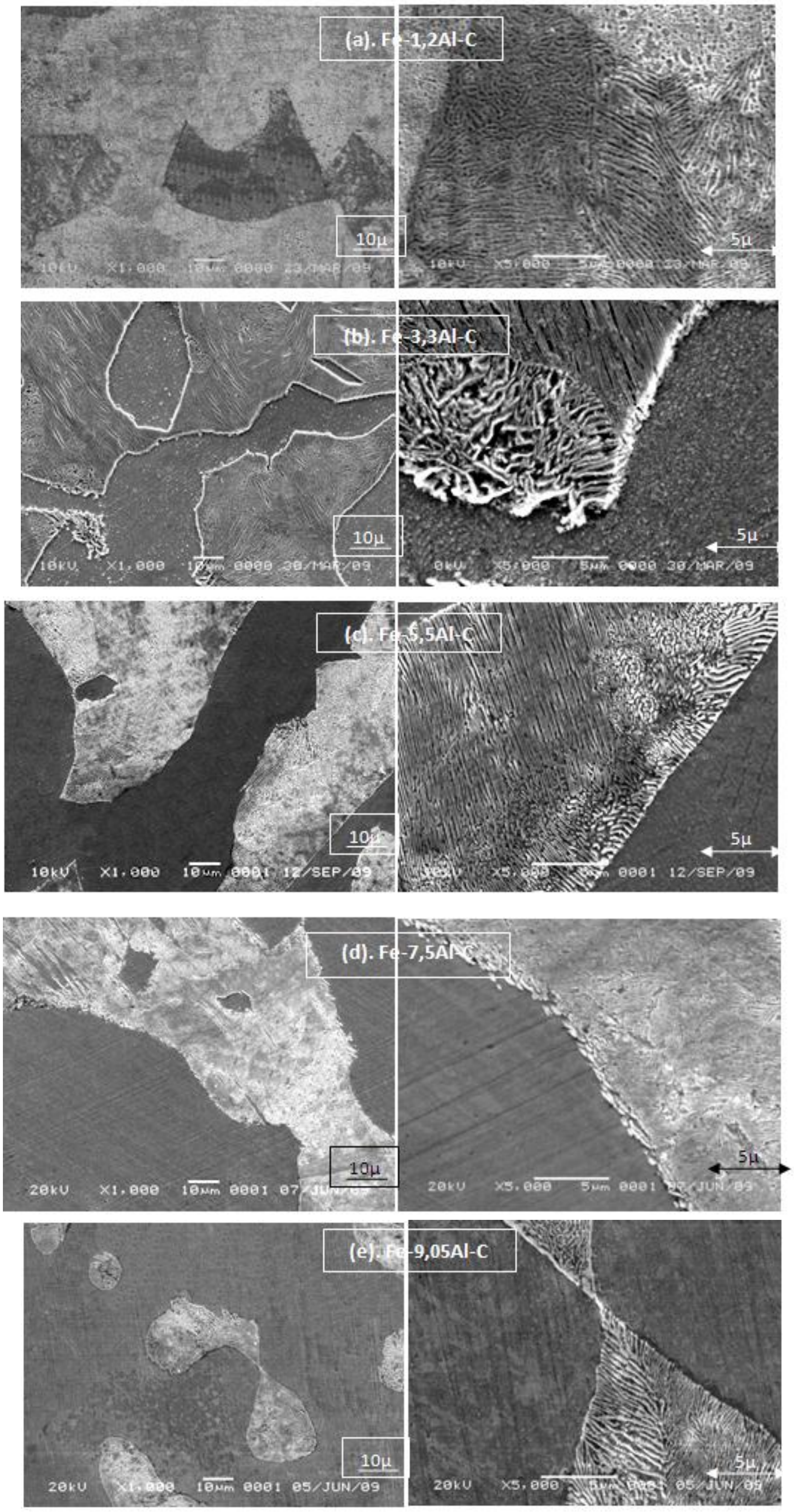

Fig. 2. Micrograph (SEM) microstructure of as cast alloys Fe-Al-C

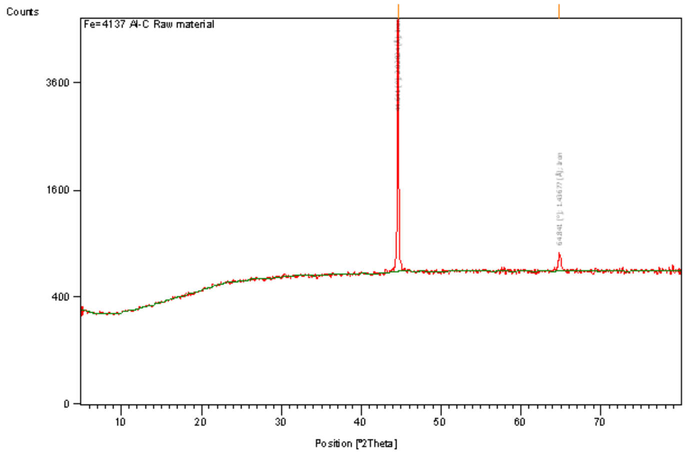

Fig. 3. XRD pattern of Fe-Al-C alloy

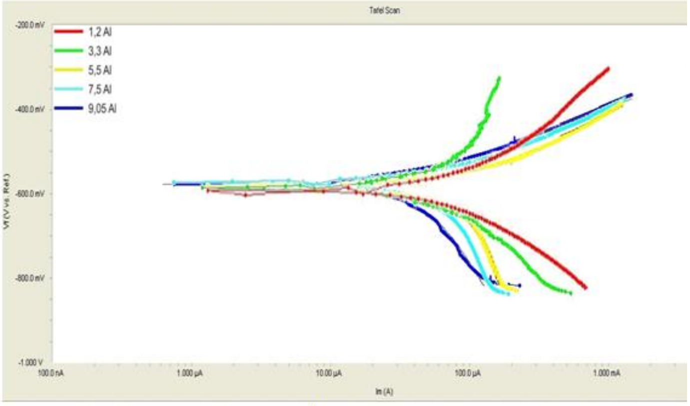

Fig. 4. Polarization curve of Fe-Al-C alloy

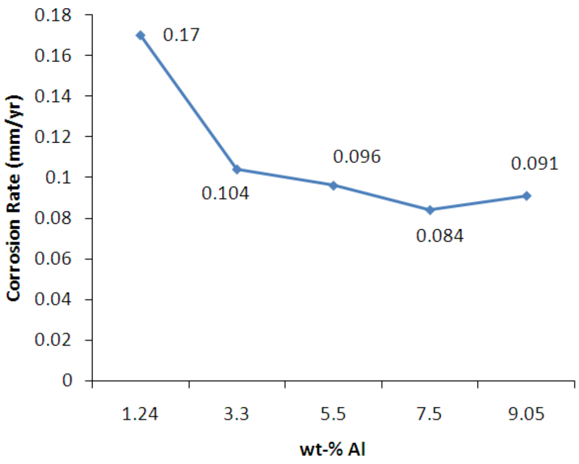

Fig.5. Corrosion rate of Fe-Al-C alloy

Table 1. Chemical composition alloys, wt-%

Alloy/lement	A	B	C	D	E
Fe	Bal.	Bal.	Bal.	Bal.	Bal.
Al	1.24	3.30	5.50	7.50	9.05
C	0.55	0.54	0.55	0.56	0.56
Mn	0.62	0.63	0.62	0.64	0.64
P	0.02	0.02	0.03	0.03	0.03
S	0.03	0.03	0.02	0.03	0.03
Si	0.62	0.62	0.63	0.61	0.62
Sn	0.01	0.01	0.01	0.01	0.01

Table 2. Corrosion parameters of Fe-Al-C alloy

Alloys	I corr (µA/cm^2)	Ecorr (mV)	EW	D (g/cm^3)	CR (mpy)	CR (mm/yr)
Fe-1.2 Al-C	18.5	-597	18.76	7.69	5.82	0.147
Fe-3.3 Al-C	13.2	-580	18.18	7.54	4.11	0.104
Fe-5.5 Al-C	12.0	-577	17.86	7.25	3.81	0.096
Fe-7.5 Al-C	10.4	-562	17.54	7.10	3.31	0.084
Fe-9.05 Al-C	11.2	-571	17.24	6.90	3.61	0.091

Conclusion

Microstructure of Fe-Al-C alloy is ferrite and pearlite where the higher levels of Al ferrite phase increasingly dominant. Corrosion rate of Fe-Al-C alloy ranged from 0.084 to 0.047, where the higher levels of Al corrosion rate decreases until it reach the lowest price on the Al content of 7.5%.

Acknowledgements

The authors are pleased to acknowledge the financial support of this research by the "Hibah Bersaing" Program, Direktorat Jendral Pendidikan Tinggi, Kementerian Pendidikandan Kebudayaan, Republic of Indonesia.

References

[1] Shackelford, J.F., 1992, Introduction to Material Science for Engineers, 3th ed., McMillan Publishing Company, New York.
[2] Kim, H., Suh, D.W., and Kim, N.J., 2013, Fe–Al–Mn–C lightweight structural alloys: a review on the microstructures and mechanical properties, Scienceand Technologyof Advance Materials.Vol.14 No.1
[3] Frommeyer, 2000, Physical Mechanical PropertiesIron-Aluminum-(Mn-Si) Lightweight Steels, The 1999 ATS International Steelmaking Conference,

Paris. Sec.4.

[4] Huang, B.X., Wang, X.D., Rong, Y.H., Wang, L., and Jin, L., 2006, Mechanical behavior and martensitic transformation of an Fe–Mn–Si–Al–Nb alloy, *Materials Science Engineering* A 438-440 p. 306-311

[5] Kobayashi, S., Zaefferer, S., Schneider, A., Raabe, D., danFrommeyer, G., 2005, Optimisation of Precipitation for Controlling Recrystallization of Wrought Fe3Al Based Alloys, Intermetallics, 13, 1296-1303.

[6] Jablonska, M., Jasik, A., danHanc, A., 2009, Structures and Phases transitions of The Alloys on the bases of Fe-Al Intermetallic Phases, International Scientific Journal vol. 29. Issue 1, p.16-19.

[7] Baligidad, R.G., Prakash, U., Ramakrishna Rao, V., Rao, P.K., danBallal N.B., 1996, Effect of Carbon Content on Mechanical Properties of ElectroslagRemelted Fe3Al Based Intermetallic alloys, ISIJ, Vol. 36, No. 12, 1453-1458.

[8] Baligidad, R.G., Prakash, U., danRadha Krishna, 1998, Effect of Carbon Addition on Structure and Mechanical Properties of ElectroslagRemelted Fe-0wt.% Al alloy, Vol. 249, No. 1-2, 97-102.

[9] Baligidad, R.G., danSatya Prasad, K./2007, Effect of Al and C on Structure And Mechanical Properties of Fe-Al-C alloys, Materials Science And Technology, vol 23, no. 1, p 38-44.

[10] Parker, S.H.F., Grundy, P.J., Jones, G.A., Briggs, I. dan Clegg, A.G., 1988, Micro structural and Magnetic Properties of the Permanent Magnet Material Fe-Al-C, Journal of Material Science, Vol. 23, Hal. : 217-222.

[11] Kao, C.H., dan Wan C.M., 1988, Effect of Manganese on the oxidation of Fe-Mn-Al-CAlloys, Journal of Materials Science, Vol. 23, Hal.: 744-752.

[12] Giza, K., Bala, H., Wysocki, J.J., and Szymura, S., 1999, Corrosion Resistance of Fe-Al-C Permanent Magnet Alloy, Intermetallic, Vol.6, issue 5, p.357-362.

[13] Chao, Y.C., and Liu, C.H., 2002, Effect of Mn Content on the Microstructure and Mechanical Properties of Fe-10Al-xMn-1.0C Alloy, Materials Transactions, Vol. 3, No. 10, pp. 2635-2642.

[14] Honeycombe, R.W.K. danBhadeshia, H.K.D., 1995, Steel Microstructure and Properties, 2nd ed., Edward Arnold, London.

[15] Shankar Rao, V., 2004, High Temperature Oxidation Behavior of Fe-Al-C alloys : an Overview, Materials Science and Engineering. A, Vol. 364, No. 1-2, pp 232-239.

[16] Tjong, S.C., 1986, Stress Corrosion Cracking behavior of the duplex Fe-10Al-29Mn-0, 4C alloy in 20% NaCl solution at 100°C, Journal of Material Science, Vol. 21, Hal.: 1166-1170.