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Strengthening Aluminum Scrap by Alloying with Iron

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Abstract

The aim of this research is to experimentally study the effect of strengthening aluminum scrap by iron powder in order to achieve better mechanical properties. Aluminum scrap is melted in a heated furnace to form a melt composition. The melt is adjusted to form the present composition, consisting essentially of iron, 1,2,3 and 5 wt%. The alloys were made by melting scrap aluminum using an induction furnace, and then iron powder was added to the melt. The composition is then casted into steel moulds to be later machined to produce tensile tests specimens. The mechanical and metallurgical characteristics of the fabricated alloys were studied through optical, Hardness survey, and tensile testing. Superior properties were obviously manifested in the cast aluminum with 1 wt% iron addition. Ultimate tensile strength and elongation to fracture and Vickers hardness were all increased by 72 %, 60%, and 7% respectively.

Keywords: Aluminum Scrap; Iron Powder; Casting; Mechanical Properties.

1. Introduction and Literature Review

Pure aluminum is weak having a tensile strength between 90 to 140 N/mm^2, however, wrought aluminum in its alloyed form has higher strength and is similar to structural steels. It is mainly used for electrical conductors and for domestic products, however, for structural use it has to be strengthened by alloying [1].

Aluminum alloys are used extensively in making mechanical parts due to its high specific strength (strength/density). The main usage of aluminum alloys are in applications requiring light weight materials as in aerospace industries and in automotive industries. The second important property of aluminum is its resistance to corrosion. Aluminum has a strong protective oxide layer which prevents continues corrosion of the base material. Therefore, a lot of work is done to achieve better properties of aluminum by alloying, heat treatment and other processes. On the other hand aluminum has a big disadvantage of having a low melting temperature which put limits on the temperature range of applications

Aluminum can be recycled, it retains a high scrap value. It can be recycled indefinitely without losing any of its superior characteristics, making it especially appealing according to both environmental and economic criteria

Aluminum recycling saves 95 percent of the energy required to produce aluminum from raw materials. Conserving natural resources is important; because it takes four pounds of bauxite ore to produce one pound of aluminum, every pound of recycled aluminum saves four pounds of ore. Increasing the use of recycled metal has an important effect on the CO2 emission, since producing aluminum by recycling produces only about 4% as much CO_2 as by producing it from natural resources [2,3].

Iron is the most common impurity found in aluminum. It has a high solubility in molten aluminum and is therefore easily dissolved in the liquid state of aluminum, however its solubility in the solid state is very low (~0.04%). The low solubility of iron in the solid state is accompanied by decreased ductility as a result of the formation of intermetallic phases like FeAl and/or Fe_3Al. These intermetallic phases increases the strength of the aluminum alloy they also enhances corrosion resistance. [4,5].

The most difficult elements to control in the recycled aluminum is Fe and Si and these elements tend to increase slightly the more often the metal has been recycled. Fe in particular has a higher tendency to increase gradually in metal recycled over and over again, primarily from pickup from scrap handling systems. As a result, Fe is an ideal candidate for application to alternative products, a good example of which is the use of increased Fe content in aluminum as a deoxidizing agent for steel production. This would benefit both the aluminum and steel industries and add to the life-cycle benefits of aluminum operations [6]. Another example of using high Fe bearing aluminum is to make use of the affinity of Zr for Fe, creating a heavy particle readily taken from an aluminum melt [6].

The mechanical behaviour of an alloy based on Fe-40A1 prepared from mechanically alloyed powders was examined over a wide temperature range in the fine-grained, as-extruded state as well as after recrystallizing to a large-grained state by Morris and Gunther in 1995 . They found that the fine-grained material was strong and reasonably ductile at room temperature, in contrast with the weaker and more brittle large-grained material. At high temperature the strength fell to low values, similar for both materials. They related that behaviour to the contribution of strengthening due to the particles present [7]. Sasaki *et. al., in 2009,* consolidated Nanocrystalline Al–5 at.% Fe alloy powders produced by mechanical alloying by spark plasma sintering. The sintered sample showed high strength with a large plastic strain of 15% at room temperature and 500 MPa at 350 ºC. A range of mechanical properties have been investigated for non-hardenable aluminium alloys [8]. Zander et. al., in 2007, took into account in their study *the* particle strengthening and work hardening the models solid solution. Morris *et. al.,* in 2006, descovered a new iron–aluminium alloy with zirconium and chromium additions that forms fine coherent precipitates on annealing cast material that remain very fine even after extended annealing at temperatures as high as 900 ºC. Using this new model they could improve high-temperature creep stresses.

In this study aluminum and iron powder were processed by casting into rectangular shaped samples. Iron powder was added to molten aluminum to obtain a two phase material consisting of aluminum matrix and a second dispersed iron aluminide phase. The solubility of iron in aluminum is almost negligible at room temperatures this in turn results in a composite material of more than one phase. The strength of the resulting material will depend mainly on the amount of the iron aluminides present in the microstructure. The properties will also depend on the amount of other alloying elements found the material.

In order to optimize the material properties for certain applications it is necessary to study the cast structures. In the present work this has been done for iron aluminides. The results are discussed with respect to material parameters like composition.

Generally recycling needs a significant challenge in shredding, sorting, and, in some cases, further refining of the metal to achieve acceptable impurity levels. Fe in particular can be a significant challenge.

Aluminum scrap is refined by separation processes that increase metal purity such as the segregation method, the solid solution separation method, the temperature gradient method, the eutectic separation method, the inter-metallic compound method, the gravity separation method, etc. These methods, however, are difficult to apply to the manufacturing systems because of low efficiency, complicated apparatus, high cost and environmental contamination [11]. This puts high demands for innovative separation technologies to improve the sorting, and thereby the quality, of scrap. Another approach is to reduce significantly the amounts of various elements that occur in scrap, the nearly universal alternative for controlling such elements in recycled aluminum alloys is to dilute them with purer alloy grades or virgin pig [12].

2. Materials, Experiments, and Characterization

2.1. Materials

Scrap aluminum consisting mainly of electrical cables having the composition shown in table 1, was first melted and then iron powder was added to the melt. The amount of powder added and the total composition of the mixture is shown in table 2. The iron powder has the commercial designation ASC 100 delivered by Höganäs AB, Sweden. The powder is a water atomized iron powder having a packing density of ≈ 3 g/cm^3 and a particle size range between 20 to 150 µm.

Table 1. Chemical composition (wt-%) of the aluminum alloy used in electrical cables

Al	Si	Fe	Cu	Ti	V	Mn
99.84	0.0517-0.0361	0.1256-0.0728	0.0017-0.0007	0.01-0.0075	0.01-0.0075	0.003-0.0006

Table 2. Composition (wt-%) of the five alloys investigated

Alloy	wt% Scrap Aluminum	wt% ASC 100
1	100	0
2	99	1
3	95	5
4	90	10
5	85	15

2.2. Experimental Procedure

The successive stages of casting the aluminum scrap are:

Firstly the aluminum cables were cut into small pieces and then they were cleaned from surface oxides by a sand plaster machine. This was done to reduce the amount of slag present in the molten metal and to avoid or minimize the oxide present in the casting**.**

Secondly, the small pieces of the aluminum scrap wires were melted in a batch furnace having a maximum temperature of 1300 ºC with no protective atmosphere. This was done by heating the furnace to 1000 ºC then the aluminum scrap wires were added into the crucible.

Thirdly, when the aluminum scrap wires were completely melted the iron powder was added to the melt. The mixture was stirred continuously in order to avoid sedimentation and to achieve a more homogeneous mixture.

Finally, the mixture was then poured into a rectangular shaped mould and cold in air.

2.3. Characterization

The mechanical properties of the cast aluminum scrap were tested using an Instron universal testing machine.
The tensile testing samples were made by machining the as cast alloys using a chipping machine and a milling machine.

The microstructure of the as- cast alloys was characterized by means of an optical microscope. Sample preparation was done by wet grinding, diamond polishing and etching in a chemical solution (0.5% -1%HF. 2.5% HNO_3, 1.5%HCl, and 95.5% distilled water).

3. . Results

3.1. Mechanical properties

The results of the mechanical properties are shown in Figs, 1, 2, and 3. These figures give a summary of the obtained mechanical properties, ultimate tensile strength (UTS), elongation to fracture, and Vicker's hardness.

Figure1 shows the effect of percent iron added to aluminum on UTS. The standard deviations of the mean for the measured UTS are indicated by the scatter bands at top of the bars in the figure. Clearly, the scatter is rather high for alloy 1 and for the other alloys the scatter is rather low and a comparison between different alloys can be made. As can be seen from Figure1, the UTS increases compared to the starting alloy with increasing iron addition from 1 wt% to 5 wt% then the UTS value drops down below the UTS of the starting alloy with further iron addition. The highest obtained UTS is for alloy 2 which is about 155 MPa and the lowest UTS is for alloy 5 which is about 40 MPa.

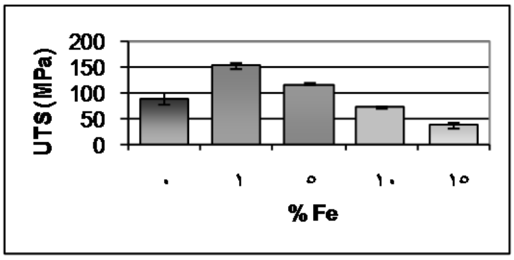

Figure 1. UTS values for the alloys studied in their as cast condition.

Figure2 shows the elongation to fracture for the different alloys. As in the previous figure, the error bars indicating the standard deviations shows that the scatter for the starting alloy is rather high thus a rough comparison can be made. The maximum elongation obtained is for alloy 2 which is about 16 % elongation to fracture and the minimum elongation is for alloy 5 which is about 0.2% elongation to fracture.

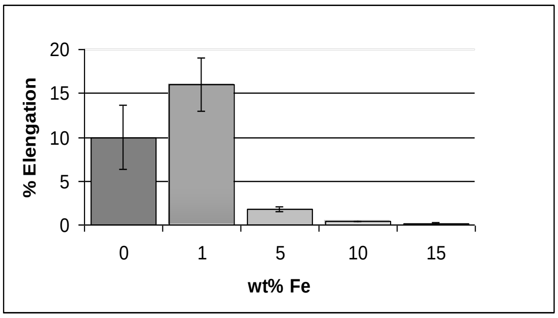

Figure 2. Elongation to fracture for the alloys studied in their as cast condition

The effect of Fe addition on the hardness of the starting alloy is shown in Figure3. The error bars indicating the standard deviations show that the scatter in measured data is such that a comparison of the measured hardness can be made for the different alloys. The measured hardness values indicate a continuous increase in hardness with increasing added iron to the starting alloy. The maximum hardness values is obtained for alloy 5 which is about 43 HV and the minimum hardness value is for alloy 1 which is about 21 HV

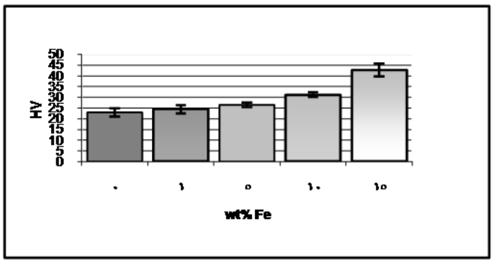

Figure 3. Vickers hardness for the alloys studied in their as cast condition.

3.2. Microstructure

Microstructural analyses were conducted by optical microscopy. The microstructures of as cast samples are given in Figures. 4, 5 and 6.

Fig.4 shows the microstructure of the starting alloy number 1. It's clear from the micrograph that the microstructure consists of grains of Aluminum. The black dots in the microstructure are mainly effects of etching and some impurities.

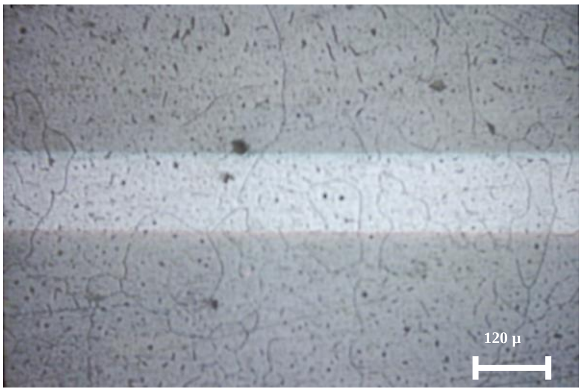

Figure 4. As cast microstructure of alloy 1 showing grain and grain boundaries of Aluminum

Fig. 5 shows the microstructure of alloy 2. The as cast microstructure of alloy 2 shown in Fig. 5 consists of two phases, the dark phase which is iron aluminide located at grain boundaries and a light phase which is aluminum grains

Figure 5. As cast microstructure of alloy 2 showing two phases the dark phase which is iron aluminide and the light phase aluminum grains

Fig. 6 shows the microstructure of alloy 3. The microstructure consists of two phases the dark phase which is iron aluminide and the light phase aluminum grains.

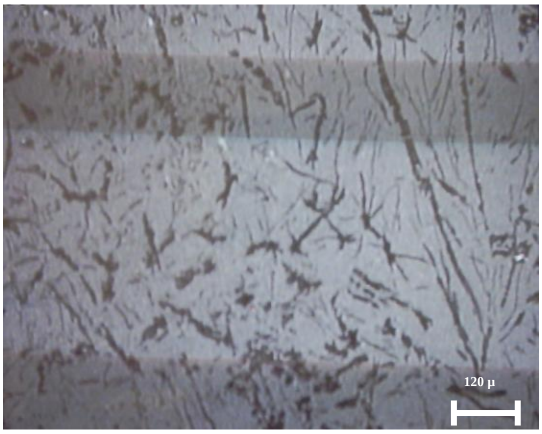

Figure 6. Microstructure of alloy 3 after sintering showing two phases the dark phase which is iron aluminides and the light phase aluminum grains.

4. Discussion

The analysis of the results shows that the effect of the 1% addition of iron to aluminum scraps has a positive effect on the mechanical properties of the aluminum scraps (UTS and elongation to fracture). This can be attributed to the precipitation of intermetallic compound on the grain boundaries of aluminum.

Increasing the amount of iron to above 1% deteriorates the mechanical properties except for hardness. This is due to the increase of the hard inter-metallic phase amount in the microstructure.

The mechanical properties of the alloys containing iron aluminides are very sensitive to the amount of iron aluminide and to factors affecting the strength of the iron aluminide like aluminum content dissolved in the iron aluminide, order (type, amount, and size), heat treatment, test temperature, and defects because Iron aluminides have limited ductility at ambient temperatures.

Considering the equilibrium binary phase diagram for aluminum and iron, as the iron content increases, the amount of the intermetallic phase Al3Fe increases too. For alloy 2 the amount of Al3Fe present is approximately 4% by atomic weight and for alloy 3 the amount of Al3Fe is approximately 20 % by atomic weight. The mechanical properties of iron aluminides are very sensitive to many factors including aluminum content, order (type, amount, and size), heat treatment, test temperature, alloying additions, environment, microstructure, and defects [13].

Studies have shown that the ductility of the Fe3Al-based aluminide can be substantially improved by increasing aluminum content from 25 to 28% [14]. Thus by increasing the amount of iron in the alloys studied the amount of aluminum in the intermetallic phase decreases leading to a decrease in ductility.

The mechanical properties of the starting alloy with no iron addition showed inferior properties. This can be attributed to the fact that the microstructure is made up of coarse grains as shown in Fig.4. Adding iron to Aluminum causes grain refinement which is evident from alloy 2 where superior mechanical properties is obtained compared to the starting alloy. According to ref. [15] adding 0.5 wt% Fe content to pure aluminum caused the most effective grain refinement compared to the other iron contents.

From the finding of this work it can be stated that instead of refining the aluminum scrap by expensive means or by controlling the composition of aluminum scrap by diluting elements found in the scrap with purer alloy grades or virgin pig, enhancing the mechanical properties by alloy addition like the addition of iron as in the case of recycled electrical wires is a more economical and less time consuming process.

5. Conclusions

- Superior properties were obviously manifested in the cast aluminum with 1 wt% iron addition. Ultimate tensile strength and elongation to fracture and Vickers hardness are increased by 72 %, 60%, and 7% respectively at ambient temperature.
- The low ductility of the used aluminum scrap is due to its coarse grain structure

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