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Production of high-resistivity electrical steel alloys by substitution of Si with Al and Cr

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1. ABSTRACT

Fe-3Si-3Al and Fe-4Si-4Cr (wt%) experimental alloys were processed to assess the electrical resistivity and workability effects of substituting Al and Cr for Si in high-Si electrical steel alloys. The experimental alloys were made by arc melting, and processed by hot rolling and cold rolling to produce strips. Samples were characterized by means of metallography, hardness, workability and resistivity. Results showed that the two alloys could be rolled down to 200 µm thickness (90% hot rolled reduction and 80% cold rolled reduction) without crack formation in the strips. Hardness in the annealed condition and electrical resistivity were 228 HV/74 µΩ·cm and 243 HV/85 µΩ·cm, respectively, for the Fe-3Si-3Al and for Fe-4Si-4Cr alloys. The resistivity measured for Fe-4Si-4Cr was higher than the resistivity reported for the benchmark high-Si alloy, Fe-6.5Si. Both experimental alloys showed improvement on the workability compared to Fe-6.5Si since there was no edge cracking on the cold-rolled strips up to 80% percent reduction, and the hardness was approximately 35% lower.

2. INTRODUCTION

Electrical steel as a soft magnetic material is essential in the modern world due to its important role in power generation, transformation and use. From transformers to electrical motors, electrical steels containing up to ~ 3.2 wt % are used as a magnetic core material to improve the working efficiency of these machines [1,2]. For many years, researchers have demonstrated that Fe–6.5 Si wt% is an optimal alloy composition to improve as much as possible, the magnetic flux, and to increase the resistivity of the steel, thereby reducing core losses. However, addition of high-resistivity alloying elements drastically reduces the steel workability, hence making the manufacturing of alloys with Si content higher than 3.5 wt% impractical by traditional rolling [3,4]. These workability constraints have been the principal driver for using steels with reduced Si content in current applications, therefore losing the opportunity to achieve better magnetic efficiencies. Alternative methods have been developed to produce Fe-6.5Si wt% sheets. A commercial example is Fe-6.5 wt% sheet produced by CVD coating of Si on Fe-Si sheet and diffusion annealing. Most of these methods have not had a considerable impact in applications primarily because of cost and production economics. Furthermore, the magnetic properties of the steels produced by these approaches also do not show properties characteristic of the rolled high-silicon alloys [5-9].

Reducing core loses on electrical steels is one of the main ways to improve efficiency in power transformation machines. Core losses are composed of eddy current losses, hysteresis losses, and anomalous losses, which increase with increasing frequency. Eddy current losses are reduced by increasing electrical resistivity, most effectively through solid solution alloying additions. Whereas, hysteresis losses are affected also by microstructure modifications such as grain size, and texture [10, 11]. At frequencies of approximately 50 Hz the ratio of hysteresis losses and eddy current losses is close to 1:1. The higher the frequency, the higher the eddy current losses compared to the hysteresis losses [12, 13].

For this study, Fe-3Si-3Al and Fe-4Si-4Cr (wt%) are proposed as alternative alloys to substitute for the well-known high performance of Fe-6.5Si. The goal was to obtain an alloy with the high resistivity of Fe-6.5Si (at least 80 μΩ·cm) but better workability for sheet production. The dramatic effect of Si on the loss of ductility in iron is well known. In general, this poor ductility (workability) above about 4% Si has been attributed to a B2 ordering due to the dissociation of superlattice dislocations induced by the high Si amounts in the material [4]. Silicon is the most potent alloying element to increase the electrical resistivity of iron. However, aluminum and chromium are also effective alternatives [14, 15]. Moreover, Fe-Al and Fe-Cr phase diagrams show that other than the gamma loop typical of iron alloys, there is no other type of ordering or phase transformation up to 10 wt% for the Fe-Al system and more than 20 wt% for the Fe-Cr system. Additionally, Fe-3Si-3Al and Fe-4Si-4Cr seem to be in the α-Fe region based on the available ternary phase diagrams [16,17]. Actually, previous studies have demonstrated that if the correct thermomechanical procedure is followed (hot rolling down to 1 mm + cold rolling), thin sheets of Fe-Si-Al alloys can be produced [18-20]. However, there is no solid agreement about how much Si+Al can be added and still maintain good cold workability, i.e., before the alloy gets too brittle. Some authors claim that Si+Al has to be lower than 3.5 wt%, but some others say that even Fe-6.5(Si+Al) is possible if the correct procedure is followed [13,21]. Information about the workability of alloys in the Fe-Si-Cr system is limited, as is any type of resistivity information about this alloy.

3. EXPRIMENTAL PROCEDURE

3.1 MATERIALS

Fe-3Si-3Al and Fe-4Si-4Cr (wt%) samples were produced in house in order to control the purity of the alloy. High purity elemental metals used to manufacture the alloys had compositions in wt.% as follows: Fe 99.98%, Si (>99.999%), Cr 99%, and Al 99.99%. The experimental alloys were made using an arc melter with a non-consumable tungsten electrode on a water-cooled copper hearth. The alloys were melted under flowing 99.99% Ar, and they were turned over and re-melted three times to obtain button shaped samples with good homogeneity. The button samples were approximately 50 g, diameter of 4 cm, and thickness of 1.5 cm approximately. The buttons were hot rolled to ~1 mm thickness, and then cold rolled down to the limit of the mills (~200 μm) to produce thin strips ~10 mm wide. The samples were heated in a box furnace in air up to 800 °C for 10 min before the first pass and in between all the passes during hot rolling. Samples were polished after hot rolling and before cold rolling to remove the small amount of oxidation.

3.2 METALLOGRAPHY

For metallographic preparation the as-cast buttons were cut using a wire EDM (Mitsubishi FX20) and the rolled strips were cut with a low-speed diamond saw. Silicon carbide paper with grits from 320 to 2000 were used to grind the samples, and a final polishing using 6 μm and 1 μm diamond paste was performed. The samples were etched for microstructure examination using 5% nital for the Fe-3Si-3Al alloys and 40% nitric acid aqueous solution for the Fe-4Si-4Cr alloy. Vickers hardness testing was performed with a load of 500 g (HV0.5) and 250 μm distance between indentations. At least 10 indentations were made for each hardness and the values are reported as the mean ± one standard deviation.

3.3 RESISTIVITY

Resistivity measurements were done following the 4-wire method of ASTM A712-14 Standard Test Method for Electrical Resistivity of Soft Magnetic Alloys. A multimeter (HP 3468B) measured the resistance of Fe-3Si-3Al and Fe-4Si-4Cr (wt%) strips with a resolution of 1 mΩ, and the geometry of the strip was measured with a Vernier caliper with a resolution of 0.01 mm. Although the conventional standard requires a minimum specimen length of 25 cm, for this study resistivity measurements were observed using shorter lengths due to restrictions on the length of strips that could be produced from the small arc melted buttons. Three measurements at 5 cm, 10 cm, and 14 cm were taken for each strip. Results showed that resistivity values were consistent for strips shorter than 25 cm.

4. RESULTS AND DISCUSSION

4.1 AS-CAST STRUCTURE

Figure 1 shows the as-cast structure of the experimental alloys. Columnar grains can be seen in both samples but there is no presence of dendritic structure. The absence of dendritic structure is likely due to the narrow freezing range of these alloys and high solidification rate in the arc melter. The figure shows that the grains for the Fe-3Si-3Al alloy are considerably larger than the grains for Fe-4Si-Cr alloy. One thing to highlight is the absence of secondary phases or inter-granular phases, which is good since these are detrimental to the alloy workability. The presence of just one phase allows for hot rolling the sample right after casting with no homogenization needed. Hardness measurements on the as-cast alloys indicated values of 267 ± 11 HV0.5 and 233 ± 10 HV0.5 for the Fe-3Si-3Al and Fe-4Si-4Cr, respectively

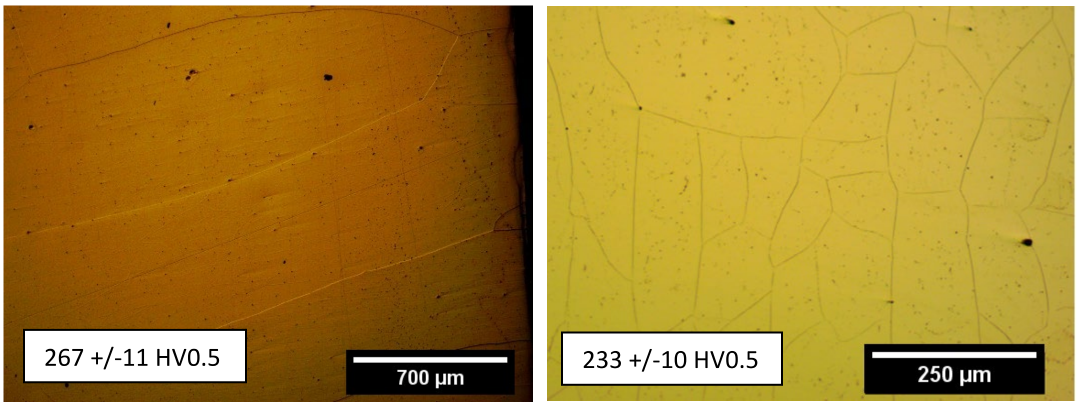

Figure 1 : Experimental alloys as-cast structure and hardness. Left) Fe-3Si-3Al. Right) Fe-4Si-4Cr.

4.2 WORKABILITY

Figure 2A and 2B show strips of Fe-4Si-4Cr wt% and Fe-3Si-3Al wt%, respectively, and figure 2C and 2D show their respective strip microstructure after rolling and annealing for 40 min at 700 °C. These strips were produced by a thermomechanical process that combines hot rolling down to 1 mm thick, and cold rolling down to the final thickness. As discussed before, some authors have contemplated the idea of more workable electrical steel alloys by substituting some Si by other elements with similar benefit for the resistivity. The experiments on the Fe-3Si-3Al alloy showed the feasibility of producing strips with a composition of Si+Al higher than 3.5 wt%, which contrasts the work presented by Stodolny and Groyecki [13]. Previous works on Fe-6.5wt% showed an improvement in the workability of the strips when hot rolling them down to 1 mm and then cold rolling the samples at the lab scale. Despite being possible to produce Fe-6.5Si wt% strips, cold rolling kept being unstable making some of the strips produced to break in the final steps [18-20]. However, in this study there was no cases of strips cracking due to cold rolling, as shown in Figure 2A and 2B.

Hardness of the alloys in the annealed condition measured 228 ± 6 for Fe-3Si-3Al and 243 ± 9 for Fe-4Si-4Cr alloy. These values are close the values for the alloys in the as-cast condition, as expected. The experimental alloys have significantly lower hardness (~35% lower) hardness reported in previous studies for Fe-6.5 Si which was around 375 HV for the as-cast condition [22]. The fact that these experimental alloys have a considerably lower hardness than Fe-6.5Si wt% in similar conditions, and having no sign of apparent edge cracking on the strips after cold rolling depict the improvement on the cold workability of these experimental alloys [23].

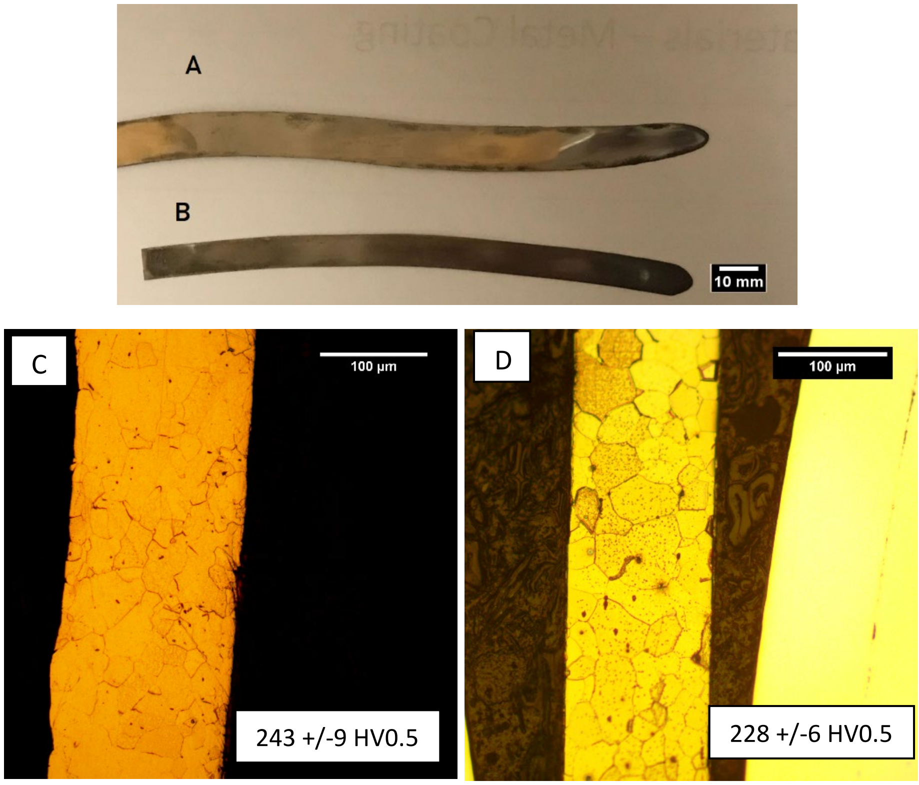

Figure 2 : Experimental alloy strips produced by hot rolling, cold rolling, and annealing. A) Fe-4Si-4Cr strip, 0.2 mm thick, and 12 mm wide. B) Fe-3Si-3Al strip, 0.15 mm thick, and 8.5 mm wide. C) Fe-4Si-4Cr strip microstructure and Vickers hardness in the annealed condition. D) Fe-3Si-3Al strip microstructure and Vickers hardness in the annealed condition.

4.3 RESISTIVITY

The resistivities measured over three different lengths were 74 ± 3 μΩ·cm for Fe-3Si-3Al wt% and 85 ± 3 μΩ·cm for Fe-4Si-4Cr wt%. The standard deviation remains below 5% of the average resistivity, which is a good indicator that the experiment is valid despite not following the 25-cm length required in the standard. The target was 80 μΩ·cm based on the resistivity of the Fe-6.5Si wt% alloy found in the literature [24,25]. Resistivity measurements for Fe-3Si-3Al wt% stayed below the target. There is a discrepancy in previous published data on the resistivity for Fe-3Si-3Al wt%. Perrier and Brissonneau [26] claimed that the resistivity for this composition should be a value of 70 μΩ·cm, while the work of Schoen and Comstock [27] predicts that the resistivity should be 80 μΩ·cm for this Fe-3Si-3Al wt% composition. The present resistivity measurements on this alloy are nearly the average of these previous predictions. It makes sense to believe that this experimental alloy would have a resistivity below 80 μΩ·cm since the Si+Al system adds up to 6%, which is lower than the 6.5% Si of the optimal electrical steel alloy. Initially it was thought that a possible Si-Al interaction could increase the resistivity up to 80 μΩ·cm, but it seems not to be the case in our experiments. On the other hand, the Fe-4Si-4Cr alloy showed a resistivity a bit higher than the targeted value. Previous resistivity data for this experimental alloy is more limited than the case of the Fe-3Si-Al wt%. The Schoen and Comstock [27] work predicts Fe-4Si-4Cr wt% should have a resistivity of 81 μΩ·cm.

However, our experiments reported a higher resistivity, showing a discrepancy as in the case of the Fe-3Si-3Al wt% alloy. The fact that the Si+Cr wt% system adds up to 8% (1.5 wt% more than the optimized Fe-6.5 wt%) could be a reason to worry about the workability of the alloy. However, the experimental results in the current paper showed that this experimental alloy is more workable than the optimized Fe-6.5 wt% alloy, and, in addition, the resistivity is higher than the target value.

5. CONCLUSIONS

The experimental alloys Fe-3Si-3Al wt% and Fe-4Si-4 wt% had columnar as-cast structure with no dendritic structure. No secondary phases were found, thus allowing rolling of the samples without homogenization. Strips of the alloys < 200 μm thick were produced by a combination of hot rolling, annealing and cold rolling, without edge cracking. Hardness of the experimental alloys in the annealed condition was about 235 HV, significantly lower than the benchmark Fe-6.5Si wt%, consistent with the higher cold workability. Fe-3Si-3Al wt% and Fe-4Si-4Cr wt% have a resistivity of 74 and 85 μΩ·cm, respectively. The resistivity of the Fe-3Si-3Al did not reach the targeted value (at least 80 μΩ·cm), but Fe-4Si-4Cr showed a resistivity higher than the Fe-6.5Si wt% resistivity. Finally, the experiments showed that Fe-4Si-4Cr alloy had a higher resistivity and sufficient workability for cold rolling.

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