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CORRELATION OF TITANIUM CONTENT AND CORE LOSS IN NON-ORIENTED ELECTRICAL STEEL SHEETS

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In this study the correlation between the titanium content of steel and the core loss of non-oriented electrical steel sheets was determined. The core loss and titanium content of steel have a weak, but positive, correlation. The core loss was found to increase with an increasing titanium content. The study included a statistical analysis of an industrial data set and a metallographic analysis of the titanium inclusions. The analyzed titanium inclusions in the electrical steel sheets containing 0,006 mas.% Ti and 0,008 mas.% Ti were complex oxycarbonitrides, complex TiC and complex Ti(C,N).

Key words: titanium, correlation, core loss, non-oriented electrical steel sheet

Korelacija između sadržaja titana u čeliku i elektromagnetskih svojstava neorijentiranih elektrolimova. U radu se opisuje korelacija između sadržaja titana u čeliku i elektromagnetskih svojstava neorijentiranih elektrolimova. Postoji relativno niski stupanj pozitivne korelacije između magnetskih gubitaka i sadržajem titana. Magnetski gubici rastu sa sadržajem titana u čeliku. Izvedena je statistička analiza podataka za limove industrijske proizvodnje i metalografska analiza titanovih uključaka. Analizirani uključci u elektrolimovima sa 0,006 mas.% Ti i 0,008 mas.% Ti bili su kompleksni oksikarbonitridi, kompleksni TiC i kompleksni Ti(C,N).

Ključne riječi: titan, korelacija, magnetski gubici, neorijentirani (dinamo) elektrolimovi

INTRODUCTION

The core loss of electrical steel is defined as the dissipation of electrical energy in the form of heat during magnetization by an alternating current. Many efforts have been made to reduce the core loss. Numerous parameters, including the chemical composition and the metallurgical technology, influence the properties of the steel.

Electrical steel sheets are mainly produced from Fe-Si-C alloys. Non-oriented electrical steels contain, in addition to the important alloying elements Si, Al and Mn, other elements as well. Non-oriented electrical steels are produced from scrap steel, and therefore impurity elements (Ti, Cu, Sn, etc.) can be found in the steel. These trace elements can influence the characteristics of electrical steels [1-4].

In this study the influence of titanium on the core loss of non-oriented electrical steel sheet was investigated. The study included a statistical analysis of the data set for the cold-rolled steel samples with different amounts of titanium. SEM and ESD were used in the metallographic analyses of the titanium inclusions.

STATISTICAL ANALYSIS

We analyzed a data set of 409 coils of non-oriented electrical steel sheet with the core loss measured at 1,5 T. The core loss ranged from 2,918 to 4,442 W/kg.

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The average chemical composition of the non-oriented electrical steel with respect to the most important alloying elements was Fe (2,18 %) Si (0,99 %) Al (mas.%).

Using a statistical analysis we determined numerical descriptive measures for the titanium content (range, mean, median, mode, standard deviation, confidence interval, coefficient of variation). We also determined the correlation coefficient between the titanium content of the steel and the core loss of the steel sheets, calculated the coefficient of determination and plotted the regression curve for the data set. The correlation coefficient and the coefficient of determination are measures of the relationship between the two variables [5].

The core loss and titanium content of the steel have a weak, positive, linear correlation.

The relationship between core loss and titanium content could also be explained by using a regression analysis.

By using the linear regression model, the magnitude of the change in the core loss (W/kg) due to a change in the titanium content is shown in Figure 1/a.

As depicted in Figure 1/a, as the titanium content increases the core loss slowly increases.

Between 0,012 and 0,014 mas.% of Ti there is an increasing step in the core loss. Therefore, a nonlinear regression model was used for a description of the relationship between the core loss and the titanium content for this population.

Table 1. **Calculated measures of the central tendency, the dispersions and the correlation coefficient between the titanium content and the core loss**

		Ti / mas.%	Core loss / W/kg
Range	Max.	0,01400	4,442
	Min.	0,00500	2,918
Mean		0,00785	3,307
Median		0,00800	3,275
Mode		0,00800	3,279
Standard deviation		0,00183	0,188
Confidence interval		0,00018	0,018
Upper limit (Ul)		0,00803	3,326
Lower limit (Ll)		0,00767	3,289
Ul - Ll		0,00035	0,036
Coefficient of variation		23,3360	5,6762
Correlation coefficient		0,26469	

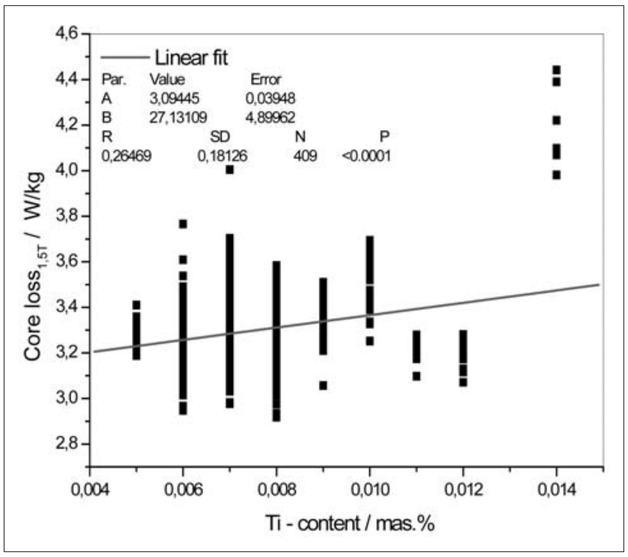

Figure 1/a. Linear correlation between core loss (W/kg) and titanium content of steel

The fitted regression curve shows an exponential growth and explains 26 % of the variance of the core loss (Figure 1/b). From a nonlinear fit we can see that as the titanium content increases the core loss slightly increases and then, after a certain point, the core loss is higher for every subsequent increase in the titanium content.

METALLOGRAPHIC ANALYSIS OF INCLUSIONS

Two samples of industrial non-oriented electrical steel sheets with an average content of titanium of 0,006 and 0,008 mas.% of Ti were used in the metallographic analysis (mean = 0,00785 mas.% Ti). The samples were

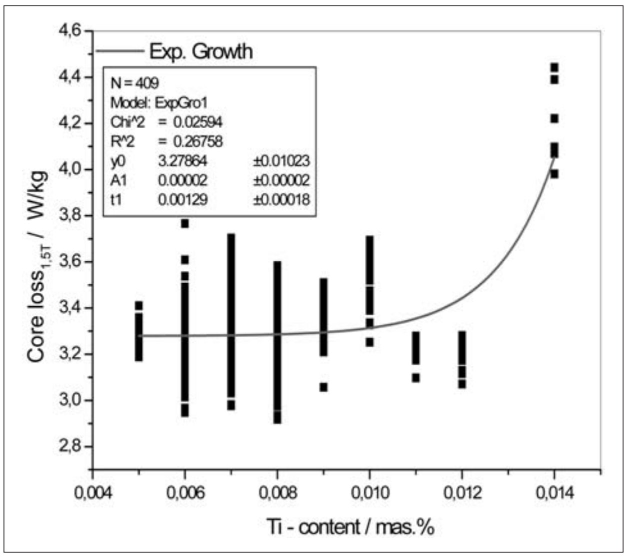

Figure 1/b. Fitted regression curve between core loss (W/kg) and titanium content of steel

ground and polished. Scanning electron microscopy and EDS were performed to analyze the titanium inclusions.

The EDS analysis revealed that the major part of the non-metallic inclusions that contain titanium are very complex. The inclusions containing titanium were predominantly small in size (< 1μm). Inclusions with different contents of titanium can be seen in Figures 2, 3 and 4.

Figure 2 represents the complex inclusions in the steel containing 0,006 mas.% Ti. The results of an EDS analysis are shown in Table 2.

We can see that the inclusions that contain small amounts of Ti are very complex (Table 2). The inclusions contain even more zirconium than titanium. The high oxygen and zirconium contents of the inclusions reveal the presence of zirconium oxides. Besides this, also magnesium and calcium, which have a strong affinity for oxygen, were detected in these complex inclusions (Table 2, Spectra 1-4). Spectrum 5 in Figure 2 shows the EDS analysis of the steel matrix.

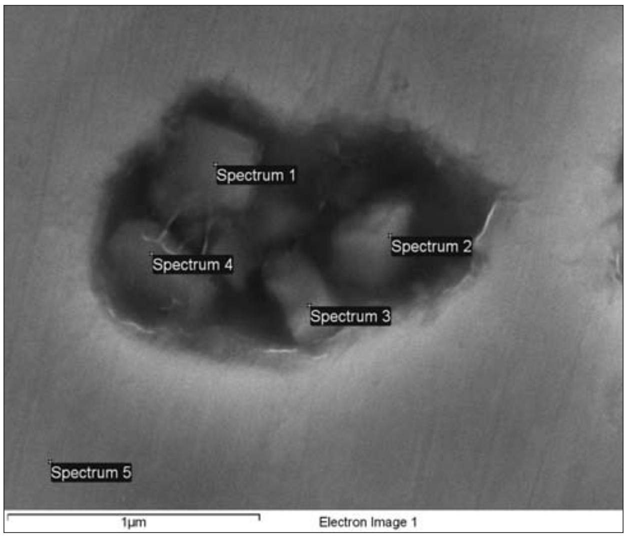

Figure 2. Complex inclusions in the sample of non-oriented electrical steel sheet containing 0,006 mas.% Ti

Table 2. **EDS analysis of inclusions from Figure 2**

Spectrum	In stats.	C	N	O	Mg	Al	Si	Ca	Ti	Cr	Fe	Zr	Total
Spectrum 1	Yes	6,51	7,61	4,16	2,66	0,32	1,09		3,83		56,49	17,34	100,00
Spectrum 2	Yes	10,03	5,81	5,43	2,42	0,59	1,25		3,72		55,67	15,06	100,00
Spectrum 3	Yes	8,10	4,52	4,71	2,10	0,51	0,98		4,04		63,68	11,36	100,00
Spectru m 4	Yes	5,73	7,31	2,32	1,82	0,43	0,90	0,31	2,48		65,53	13,15	100,00
Spectrum 5	Yes	1,90				0,78	2,10			0,44	94,78		100,00

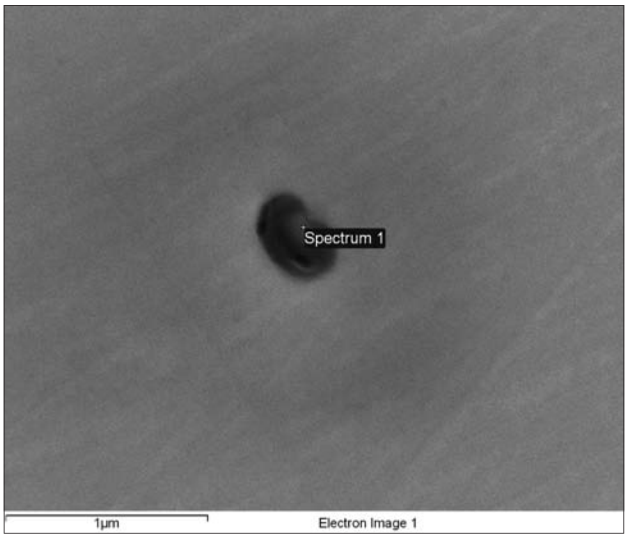

Figure 3. A Ti(C,N) inclusion in the sample of non-oriented electrical steel sheet containing 0,008 mas.% Ti

Table 3. **EDS analysis of inclusion from Figure 3**

Spectrum	In stats.	C	N	Al	Si	Ti	Fe	Zr	Mo	Total
Spectrum 1	Yes	9,36	4,07	0,66	1,33	10,54	72,23	0,94	0,87	100,00

A higher Ti content in the inclusion could be detected in the inclusion presented in Figure 3. The results of the EDS analysis are given in Table 3.

The analyzed inclusions in Figure 3 are complex Ti(C,N) and complex TiC (Figure 4), which also contain small amounts of other impurity elements like zirconium, magnesium and molybdenum (see Tables 3 and 4).

DISCUSSION

The metallurgy of steels for magnetic applications is very complex. The silicon steels for non-oriented electrical steel sheets are nowadays produced from scrap steel that contains many impurity elements [1-4]. One of these impurities is titanium. Impurity elements must be controlled during melting. It is well known that they can strongly influence the recrystallization by "pinning effects" and precipitation in both grains and grain boundaries, and therefore can also have an influence on the grain growth, texture formation and the final magnetic properties of non-oriented electrical steels [6, 7].

This study has followed the magnetic properties of a representative data set of non-oriented electrical steel sheets from industrial production. Our investigation was focused on a determination of the influence of titanium content in Fe-Si-Al alloys on the magnetic properties of the non-oriented electrical steel sheets. It was confirmed that the correlation between the titanium content of the steel and the core loss is weak, but positive.

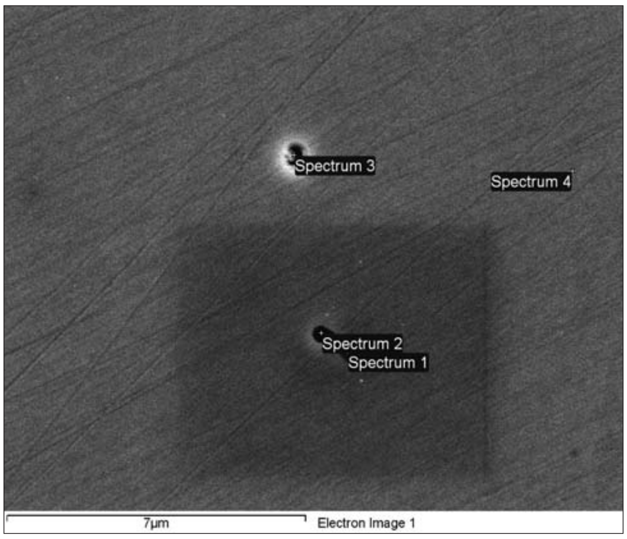

Figure 4. Titanium inclusions in the non-oriented electrical steel sheet with 0,008 mas.% Ti

Table 4. **EDS analysis of inclusions from Figure 4**

Spectrum	In stats.	C	O	Mg	Al	Si	Ti	Cr	Fe	Zr	Total
Spectrum 1	Yes	7,27		0,24	0,63	1,51	14,89		74,05	1,40	100,00
Spectrum 2	Yes	4,07	1,31		0,73	1,47	0,59		91,83		100,00
Spectrum 3	Yes	3,11			0,58	1,59	0,95	0,50	93,28		100,00
Spectrum 4	Yes	2,60			1,01	2,11			94,28		100,00

Linear and nonlinear regression models were used to describe the relationship between core loss and titanium content for this population. From both fits we can see that as the titanium content increases the core loss increases. Furthermore, there is an increasing step in the core loss after a certain content of titanium in the steel (0,012 – 0,014 mas.% Ti).

The magnitude of the change in the core loss (W/kg) due to a change in the titanium content could be better described by a nonlinear fit. Using a nonlinear fit the core loss of the steels containing more than 0,012 mas.% Ti is higher for every subsequent increase in titanium content. The fitted regression curve explains 26 % of the variance of the core loss and shows an exponential growth.

The results of our metallographic analysis revealed that the titanium in non-oriented electrical steel sheets was present in the form of very complex inclusions (oxycarbonitrides) and, in addition, in the form of small and complex carbonitrides and carbides.

A disproportionately increased step in the core loss when the content of 0,012 mas.% Ti was exceeded could be the consequence of the increased cumulative (total) value of the impurity elements in the steel. Impurities can have a synergy effect on the deterioration of the magnetic properties. Titanium represents just one of many impurity elements that can enter the steel through scrap steel during recycling and through other processes of secondary metallurgy.

Titanium has a strong affinity for carbon and nitrogen and forms very stable carbonitrides [8]. It is reported that titanium carbonitrides inhibit the grain coarsening during the recrystallization of semi-processed non-oriented electrical steel sheets and deteriorated the magnetic induction and core loss [7]. On the other hand, very small precipitates of Ti(C,N) (< 30 nm) in the final products of non-oriented electrical steel sheets should not have this harmful effect [9].

Using SEM/EDS in this study it was possible to determine the presence of titanium in the non-metallic inclusions. Due to the limitations of this method we could only analyze the bigger inclusions and precipitates, with diameters of several 100 nm.

It is assumed, therefore, that the main cause of the positive correlation between titanium content and the core loss of the investigated set of non-oriented electrical steel sheets may be due to the presence of titanium inclusions and precipitates. Impurity elements are normally present in steels in the form of inclusions or precipitates and are very often harmful to the magnetic properties. Also, the texture formation might be influenced by the presence of those precipitates [6, 7].

These precipitates can influence the secondary recrystallization and the grain size of the investigated electrical steel sheets. The efficiency of the recrystallization and grain growth is very important in the production of non-oriented electrical steels. The contribution of those two production phases to increase or decrease the final core loss is, nevertheless, of great importance [10 - 14].

To ensure improved magnetic properties of the non-oriented electrical steel sheets the content of the impurity elements and the inclusions should be rigorously controlled and minimized.

CONCLUSIONS

The correlation between the titanium content of non-oriented electrical steel sheets and the core loss measured at 1,5 T was determined. The core loss and titanium content of the steel have a weak, positive correlation.

From the regression analysis we can see that there is a critical value of titanium content that influences the core loss of the non-oriented electrical steel sheets. A disproportionately increased step in the core loss could be the consequence of the increased cumulative (total) value of the impurity elements in the steel. Impurities can have a synergy effect on the deterioration of the magnetic properties. A higher titanium content also means a larger number of titanium inclusions and precipitates.

The study revealed that the major titanium inclusions in the non-oriented electrical steel sheet containining 0,006 mas. % Ti and 0,008 mas. % Ti were complex titanium carbides, complex titanium carbonitrides and complex oxycarbonitrides, which contained lower amounts of titanium.

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