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Methods for texture improvement in electrical steels

***Abstract**. Aiming the development of high efficiency electric motors for electric vehicles, there is strong pressure for improvement of the magnetic properties of electrical steel sheets. One of the clearest possibilities is crystallographic texture enhancement. In this review, diverse methods for texture improvement are presented and discussed. All of them have the drawback of increasing the cost of material processing.*

Streszczenie.** Materiały magnetyczne używane w pojazdach elektrycznych powinny mieć bardzo dobre właściwości. Jedną z metod ich poprawy jest polepszenie ich tekstury. W artykule przedtawiono metody poprawy tekstury oraz analizowano zalety iwady tych metod, włącznie z kosztami produkcji. **Metody poprawy tekstury blach elektrotechnicznych

Keywords: electrical steels, texture, rotating machines, electric car .
Słowa kluczowe: blachy elektrotechniczne, tekstura, maszyny elektryczne.

Introduction

The autonomy of electrical cars can be increased by basically three ways: (i) batteries improvement, (ii) vehicle weight reduction (iii) increase of motor efficiency. As batteries improvement is very difficult and slow, due to need of long time tests [1], the increase of motor efficiency is the most clear alternative. Among the options for increasing motor efficiency is the texture enhancement. There are many ways for improving the texture in electrical steels. However, all of them may increase the cost of the steels. Other clear options to motor performance enhancement, from the material point-of-view, are increase of resistivity, thickness reduction [2] and materials with zero magnetostriction.

This overview deals with improvement of the texture of commercial non-oriented electrical steels, and the needed materials for electric vehicles. The ideal texture for non-oriented electrical steels is {100} <0vw>. However, it should be noted that texture and the grain size [2] need to be optimized at the same time. Besides, the punching effect is very significant and can not be neglected [3,4]. The effect of plastic deformation is dominant [5,6] over the texture effect [7].

Punching can increase significantly the losses. Only with annealing and recrystallization, the plastic deformation is fully eliminated. The teeth are the region where high permeability is most necessary. Thus, the material should be free of plastic deformation, especially for applications where machine efficiency is really an issue.

The recrystallization temperature of steels starts at ~500^{o}C [8]. This means that total elimination of plastic deformation requires annealing at such high temperatures and, besides, the coating of steel sheets should be resistant at more than 500^{o}C. These problems may explain why the electric motor industry avoids recrystallization annealing. However, for high efficiency motors applied in electric vehicles, the total elimination of deformation in the teeth region can be a real necessity.

Another relevant issue is the anisotropy. Some steels have better properties at the rolling direction (usually due to Goss orientation {110} <001>, a recrystallization texture component). This can generate significant rotational losses [9]. The rotational losses depend strongly on sheet anisotropy [10].

The easy axis in bcc iron is <100>. This means that each bcc alpha-iron crystal has 3 easy axis: [100], [010] and [001]. The {100} planes have two easy axis direction parallel to the plane of the sheet. Goss grains have only one easy axis parallel to the plane of sheet. {111} direction does not have any easy direction parallel to the plane of the sheet. See Fig. 1 for illustration of the planes {110}, {110} and {111}. For better magnetic properties, the best plane is, thus {100}, which has 2 easy axis parallel to the sheet surface. The ideal texture {100} <0vw> indicates that the best situation is random distribution of these easy axis parallel to the sheet surface.

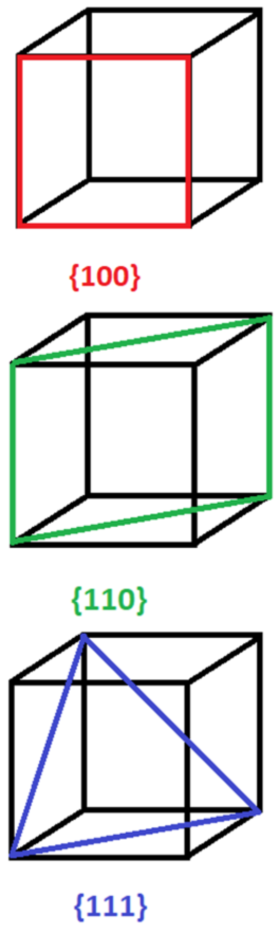

Fig.1. Illustration showing the three main families of planes in a cubic crystal: {100}, {110}, and {111}. Note that the {100} planes are on the face of the cube

Applications

As can be seen in Table I, deep drawing steels for metal forming and GO (grain-oriented) electrical steels can have very optimized texture. This is possible because texture components as {111} <uvw> and Goss {110} <001> are common recrystallization texture components of bcc iron [11,12]. However, the texture of non-oriented commercial steels is far from the ideal texture {100} <0vw> [12,13]. The {100} <001> cube on face orientation can be obtained by secondary recrystallization [14], for the case of very small thickness 0.1 or 0.05 mm [15]. This method has the drawback of producing very large grain size in spite of the {100} <001> texture [16].

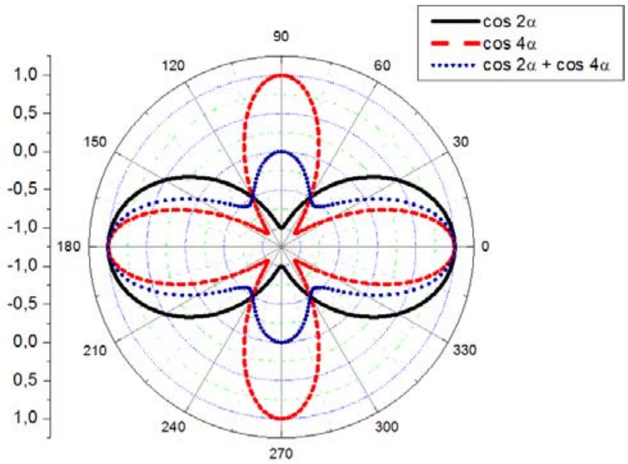

Fig.2. Graphic representation for understanding Equation (1)

The market for high efficiency non oriented electrical steels in home applications is driven by cost. Low losses non-oriented steels have applications in refrigeration and air conditioning. However, the motor efficiency can be enhanced by increasing the amount of steel in the motor core. Thus, the cost of steel is very relevant for the electric motor industry.

Thinner steels can increase significantly the cost of the motor. Not only the steel price increases with reduced thickness, but the cost for assembling the motor also increases. The number of punching steps is inversely proportional to the thickness. In applications as wind turbines, steel price is also a relevant issue. Only for electric vehicles, cost may not be a main issue.

Table I. Some Examples of Commercial Steels with optimized Texture

Type of Steel	Texture and grain size
Deep Drawing Steels (Metal Forming)	{111} <uvw> Grain size ~ 10 μm
Grain Oriented Electrical Steels	{110} <001> Grain size ~ 500 μm
Non-Oriented Electrical Steels	{100} <0vw> Grain size ~ 100-150 μm (for 50-60 Hz)

Old models of hybrid cars as Prius 2004 and Prius 2010 used electrical steels with gauge above 0.3 mm. However, steel manufacturers are now mentioning 0.2 mm, 0.15 mm and even 0.1 mm. It is possible that for saving battery price and battery capacity, electric car manufacturers choose steels with very small thickness, in spite of the higher price.

The mass of electric steel inside motors of electric and hybrid vehicles is typically of the order of 20-30 kg. Tesla Model S complete motor weighted 32 kg (or 70 pounds). If electric cars started to be produced in a very large scale, the demand for low losses thin steels can increase considerably.

A relevant question is: What material electrical engineers do prefer for electric motors? Or, without any cost limitation, what is the choice material?

The answer can be deduced by observing the favorite material used in race competions.

For example, a competition vehicle has chosen a FeCo alloy, named 1J22 [17], with 0.1 mm thickness. This alloy has chemical composition 49%Fe-49%Co-2%V (iron-cobalt-vanadium). This shows the relevance of high magnetization of saturation (2.35 Tesla) for electric machines. The 49Fe49Co alloys with 2%V are a typical choice in electric car competitions [18]. It is important to add that it is very easy to develop {100} textures in iron-cobalt alloys [19], [20], [21]. Development of cube on face {100} <001> is easier for fcc alloys, because this is the recrystalization texture in fcc. For aircraft motors operating at 400 Hz, the Fe49Co49V2 (iron-cobalt-vanadium) alloys have been a choice material for a long time [16], more than 50 years ago [22].

However, cobalt may be too expensive for the electric car industry. The cobalt price oscilated significantly in the last two years. This motivates renewed studies on improving the texture of iron-silicon steels.

Anisotropy

Anisotropy is a problem in rotating machines. This section describes how to model anisotropy. The ideal texture for electrical steels {100} <0vw> is isotropic. As before mentioned, the rotational losses depend strongly upon sheet anisotropy [10]. Following Bunge theory [23] [24], the sheet anisotropy can be modeled with Eq. (1) [25]. The coefficients A_0, A_1 and A_2 are experimentally determined. The symmetry observed in Fig. 2 comes from bcc iron cubic crystalline structure and sheet orthorhombic symmetry.

(1) $$A = A_0 + A_1\cos(2\alpha) + A_2\cos(4\alpha)$$

From Eq. (1), a very interesting result appears: Measurements at rolling direction (0^o), transverse direction (90^o) and 45^o could be sufficient for representation of all the material, see Eqs. (2), (3) and (4). This is valid for properties that depend exclusively on K_1, the constant of magnetocrystalline anisotropy [25]. Thus, Equation (1) is good for predicting the variation with angle of B_{25} and B_{50} in non-oriented electrical steels. However, in practice, there are other sources of anisotropy, and for losses domain walls displacement processes are important and compete with domain rotation processes.

(2) $$A_0 = \frac{1}{4}\left[A(0^0) + A(90^0) + 2A(45^0)\right]$$

(3) $$A_1 = \frac{1}{4}\left[A(0^0) - A(90^0)\right]$$

(4) $$A_2 = \frac{1}{4}\left[A(0^0) + A(90^0) - 2A(45^0)\right]$$

It is noteworthy that Graphs as that of Fig 2 can be used for modelling angular variation of magnetic Barkhausen noise measurements [26]. Equation (1) describes very well the anisotropy of Grain Oriented electrical steels [27]. The magnetic properties of non-oriented electrical steels can also be modelled with Eq. (1) [28], [29]. Existence of significant amount of Goss grains in non-oriented electrical steels generates significant anisotropy in these materials [11], [12]. Reduction of the anisotropy could be achieved by avoiding Goss texture components and by increasing {100} texture components.

Texture development in steels

There are different types of textures: solidification textures, deformation textures, recrystallization textures, transformation textures. The big problem for texture optimization of non-oriented electrical steels is that, in the final step, the typical recrystallization texture components are {111} <111> and Goss {110} ,<0vw>. However, {100} components in bcc materials as electrical steels can appear as result of solidification textures [30], transformation textures [31], deformation textures – by using cross-rolling [32], and even secondary recrystallization textures [33], [34], [35]. The formation of some texture components can be summarized in Table II.

The texture for deep drawing steels is inverse to that preferred for non-oriented electrical steels. Thus, using information from reserchears specialized in optimizing deep drawing steels [36], [37]. and reasoning in inverse way gives hints about how to proceed to avoid {111} and maximize {100} and Goss texture components. For example, hot band annealing increases the amount of Goss grains, because Goss nucleate at shear bands, whereas {111} grains nucleate at grain boundaries [12].

Table II. Origin of some texture components in steels (based on Ray and Jonas [31])

Austenite (γ) recrystallization texture (γ){100} <001>
Transformation Texture from austenite (γ) to ferrite (α){100} <011> originates from Austenite (γ) recrystallization texture (γ){100} <001>
Ferrite (α) cold rolling textures <110>// RD {111} <uvw>
Ferrite (α) recrystallization textures {111} <uvw> and Goss {110} <001>
Ferrite (α) solidification texture <001>//RD
Austenite (γ) solidification texture <001>//RD

Si and Al stabilize alpha-iron (bcc). But Mn stabilizes gamma-iron (fcc). Carbon also stabilizes austenite. Thus, the information of Table III is schematic only and strongly depends on the chemical composition of the steel. Silicon strongly stabilizes the bcc alpha iron structure, in such way that the 2.5% silicon steel is ferritic since the liquidus.

Table III – Regions for hot rolling of steels (based on Tanaka [37])

High temperatures (as ~950^{o}C)	Region of recrystallization of austenite
Intermediate temperatures	Region of non-recrystallization of austenite
Lower temperatures	Region of austenite and ferrite

Annealing in vacuum can develop the {100} <001> cube on the face texture [15]. This method only can be applied for small thickness (0.05 mm or 0.1 mm), and is considered as very expensive. Other possible method is strip casting [38]. The preferential direction of dendrite growth in the bcc structure - as well as in the fcc structure - is <100> [39]. Thus, as cast materials can have the easy magnetization axis in the direction of the heat extraction. The problem is to keep the <100> direction parallel to the sheet plane during the cold rolling process. Cold rolling is interesting for developing the texture for deep-drawing steels {111} <uvw> [36], [37]. As afore mentioned, the {111} <uvw> texture is opposite to that of ideal for non-oriented electrical steels.

Rotated cube {100} <011> is stable orientation after cold rolling [40]. Thus, if a strong {100} <011> is developed at the hot band, this texture component can be kept after the cold rolling process.

Table IV – Procedure for processing of high Manganese Non-oriented Electrical Steels with improved texture

Step and temperature	
1) Hot rolling - Region of austenite recrystallization (high temperature)	With high Manganese, taking advantage of gamma recrystallization texture, {100} <001> develops
2) Phase Transformation	This {100} <001> texture component transforms in {100} <011> when gamma becomes alpha
3) Cold rolling (low temperature)	These {100} texture components can remain after cold rolling step, since the cold rolling is small.
Summary - Recommendations	The rolling processing should be done at high temperatures, avoiding Si and Al addition, and avoiding heavy cold rolling

The texture of recrystallization of austenite is cube on face {100} <001> [31]. Thus, recrystallization of austenitic steels at high temperatures can generate a very favorable texture. Alloying elements that increase the fcc region, as Mn can increase the austenite field in the Fe-C carbon phase diagram. A possible high manganese electrical steel can be proposed according table IV.

Cross-Rolling is a method extensively studied more than 50 years ago. Cross rolling works because grains with {uvw} <011> orientation rotate to {100} <011> [41]. Cross-rolling is a possibility [41], [42], many times neglected because it is difficult for large scale application. But if the sheet is cut as a square, and the cross rolling is done just before the stamping step, then the cross-rolling may be possible.

The big problem with texture optimization is that, after skin-pass of ~5% and final annealing, with full recrystallization, the previous texture can change completely. Then, it is very difficult to optimize at the same time the grain size and texture.

For non-oriented semi-processed electrical steels, the typically obtained texture is far from ideal {100} <001>. The typical recrystallization texture has as the most relevant components Goss {110} <001> and {111} <uvw> [11],[12],[13]. The presence of Goss increases the magnetic induction at the rolling direction, but also introduces strong anisotropy on the sheet [43].

However, as a feasible possibility for high silicon steels, two step cold-rolling [44], [45] is now a common place procedure in industries. A recent study [46] suggest combining strip-casting and two step cold rolling.

The strong interest nowadays for improving texture in electrical steels can be noted by a significant number of recent studies focusing on texture [28], [42], [45], [46], [47], [48].

Methods for texture improvement were reviewed more than 20 years ago by Sakakura [49] and almost 60 years ago by Pry [50]. Both reviews [49], [50] mention the feasibility of the production of {100} <001> texture materials. However, as discussed by Tumanski [51], cube on face electrical steels were commercial products of Armco Steel and Vacuumschelze in the 1970s, but they were very expensive and did not find market. The very large grain size due to secondary recrystallization process certainly is one of reasons, making these materials not adequate for high frequency applications as 400 Hz [16]. This example illustrates how relevant is the optimization at the same time of texture and grain size [2].

Conclusions

As a main conclusion, there is significant space for texture improvement in commercial electrical steels, however, with the drawback of increasing the cost of processing.

1. From the Metallurgical point-of-view:

i) Nuclei of Grains with 30-45º of misorientation have big mobility [11]. This usually destroys the previous texture.

ii) Goss grains nucleates at shear bands.

iii) {111} <uvw> grains nucleates at grain boundaries.

iv) Formation of Goss and {111} as recrystallization components is easier.

v) Formation of ideal {100} <0vw> is difficult.

vi) Industry strategy is try to minimizing {111} usually by increasing Goss components.

2. Hints for Motor Producers:

i) FeCo 48 2 %V seems to be the favorite choice of electric engineers, but it is very expensive, not affordable for large-scale applications

ii) The easy way to improve the steels for high frequency is by:

Reducing thickness (to 0.1 – 0.2 mm)

Increasing amount of high resistivity alloying elements – as Mn, Al

iii) Renewed interest in old developments as double oriented steels, with cube on face texture, or in cross-rolling.

iv) Punching Step can not be neglected – effect of plastic deformation is dominant over texture.

v) Texture and Grain Size should be optimized at the same time – this is a big obstacle for achieving perfect texture in non-oriented electrical steels.

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