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STUDY OF SECONDARY RECRYSTALLIZATION IN GRAIN-ORIENTED STEEL TREATED UNDER DYNAMICAL HEAT TREATMENT CONDITIONS

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The present study was made to investigate secondary recrystallization in grain-oriented steels annealed at short time temperature exposures with application of dynamical heating. The investigated GO steels for experiments were taken from one industrial line after final cold rolling reduction and subsequent box annealing. It was shown that application of short time heat treatment conditions could lead to complete abnormal grain growth in the investigated GO steel. The texture and microstructure obtained in the laboratory treated material is similar to that observed in the same GO steel taken after industrial final box-annealing. However, some "parasitic" grains were observed in the secondary recrystallized matrix of the laboratory treated GO steel. These "parasitic" grains possess the unwanted from magnetic properties point of view {111} orientation components.

Key words: abnormal grain growth, Goss texture, grain oriented electrical steel, coercive force

Proučavanje sekundarne rekristalizacije u čeliku s orijentiranim zrnima pri dinamičkim uvjetima toplinske obradbe. Ova studija istražuje sekundarnu rekristalizaciju u čelicima s orijentiranim zrnima odžarenim kratkotrajno, a pod utjecajem dinamičkog zagrijavanja. Istraživanja ZO čelika za eksperimente uzeti su iz jedne industrijske linije nakon konačnog hladnog redukcijskog valjanja i naknadnog žarenja u komori. Pokazano je, primjena uvjeta kratkotrajne toplinske obradbe mogu dovesti do potpuno nenormalnog rasta zrna u istraživanom ZO čeliku. Tekstura i dobivena mikrostruktura u laboratorijski obrađivanim materijalima, slični su onim primjećenih kod nekih ZO čelika uzetih nakon konačnog industrijskog žarenja u komori. Međutim, neka „parazitna" zrna primjećena su tijekom sekundarne rekristalizacije laboratorijski tretiranih ZO čelika. Ova „parazitna" zrna posjeduju nepoželjne (111) orijentirane komponente s točke gledišta magnetnih svojstava.

Ključne riječi: nenormalni rast zrna, ZO teksture, zrnato orijentirani elektro čelici, koericitivna sila

INTRODUCTION

Grain oriented silicon steel (GO) is mainly used as the core material in transformers, and it is the only product manufactured in the steel industry that applies the secondary recrystallization phenomenon. Its magnetic properties are closely related to the secondary recrystallization texture, i.e., the sharpness of {110}(001), Goss texture [1]. This sharp texture develops due to a discontinuous or abnormal grain growth of Goss grains during high temperature annealing at the end of industrial production process. This heat treatment performed for secondary recrystallization and subsequent purification from the inhibitor elements. This high temperature annealing is conducting at low heating rate (~ 25 °C/hour) up to the purification annealing temperature (~1200 °C) [2]. This is time and power consuming process as the duration of the whole process is about several tens of hours. That is why, now nearly all producers are targeting on more compact and less expensive production routes of the GO steels.

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Although it is a matter of intensive basic and applied research since more than 50 years, there is no general agreement on the origin of preferred growth of the Goss grains during final box annealing. There are two similar but competing views frequently repeated in the literature of the subject. The first one originates in the suggestion that the coincidence site lattice (CSL) misorientation relationships are a factor in the secondary recrystallization in silicon steel [3]. Briefly, according to the model, the boundaries of Goss oriented grains are more frequently of the CSL-type than boundaries of other grains [3]. Moreover, in the presence of precipitates, the CSL boundaries are assumed to be more mobile than general boundaries. Thus, the Goss grains have the opportunity to grow. The second view is based on the assumption that the high mobility is a feature of the so called "high energy" (HE) boundaries defined there as boundaries between grains misoriented by the angle of 20 to 45° [4].

Again, the advantage of the Goss grains would come from the fact that they are bounded by the HE boundaries more frequently than other grains.

Table 1 *Chemical composition of the investigated sample / wt.%.*

Sampl.	C	Mn	Si	Cu	P	S	Al	N
G	0,032	0,23	3,31	0,5	0,011	0,007	0,017	0,008

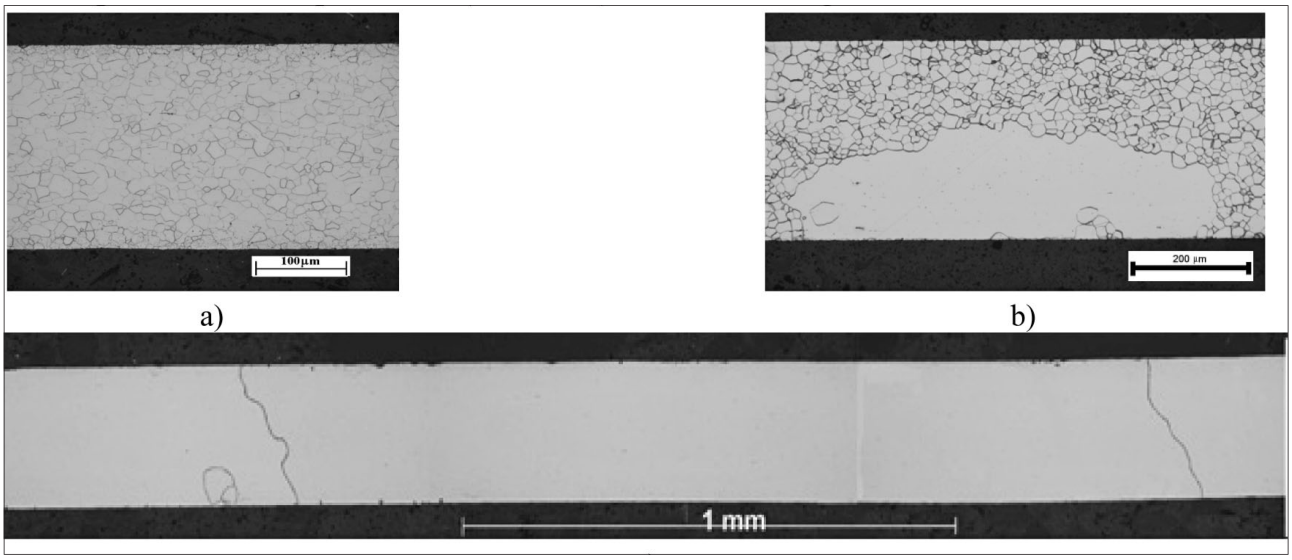


Figure 1. Microstructure of G samples annealed at a) 850 °C and b) 1000 °C c) 1025 °C for 5 min in wet atmosphere of cracked ammonium (d.p.∼ +30 °C).

The main objective of the current work is to analyze the application of dynamical heat treatment conditions to GO steels. The second purpose of the paper is to discuss secondary recrystallization during short time annealing on the base of the aforementioned hypotheses.

EXPERIMENTAL PROCEDURE

Grain oriented steels were used in the experimental procedure. The investigated G and FG steels were taken from one industrial line after cold rolling and subsequent final box annealing respectively. The cold rolling process was conducted with total reductions in thickness of 92 %. The chemical composition of the investigated steel is presented in Table 1.

Usually, to obtain desired magnetic properties, cold rolled GO electrical steels are subjected to decarburization annealing with subsequent long-time box annealing. Such industrial treatment process was realized on FG material. During the industrial decarburization the carbon level was reduced up to 0,006 % in wt. The final texture and microstructure state of the FP material was obtained after industrial box annealing.

The heat treatment of cold rolled sample G was realized by furnace “Nabertherm” with an electronic control system C19/S19. The dynamical heat treatment conditions were applied in order to investigate microstructure and texture development under such conditions. The specimens of the G steel were treated in wet decarburizing atmosphere (d.p.∼+30 °C). The investigated samples were heated up to elevated temperature with dynamical heating (heating rate ∼17 °C/s). Holding time at the annealing temperature was 5 min. Annealing temperatures were changed in the range of 850 °C up to 1100 °C.

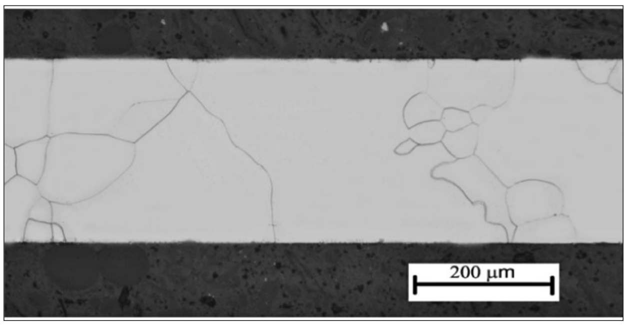


Figure 2. Microstructure of G sample annealed at 1100 °C for 5 min in wet atmosphere of cracked ammonium (d.p.∼ +30 °C).

Microstructure of the investigated specimens was examined in the longitudinal cross-section and in the normal direction plane using light microscopy. Crystallographic texture study was performed by EBSD method. JEOL JSM 7000F FEG scanning electron microscope was employed to perform the texture analysis. The patterns formed from back scattered electrons were detected by “Nordlys” EBSD detector. The obtained EBSD data were analyzed and displayed by CHANNEL-5, HKL software package.

RESULTS AND DISCUTION

Grain growth progress in material G treated in the temperature range of 850 °C – 1025 °C is shown in Figure 1. As one can see, the microstructure is fully recrystallized after annealing at 850 °C/10 min in the wet atmosphere of cracked ammonia (Figure 1a). The increase of temperature initiates the abnormal grain growth (AGG) as shown in Figure 1b. Further increase of the temperature provides

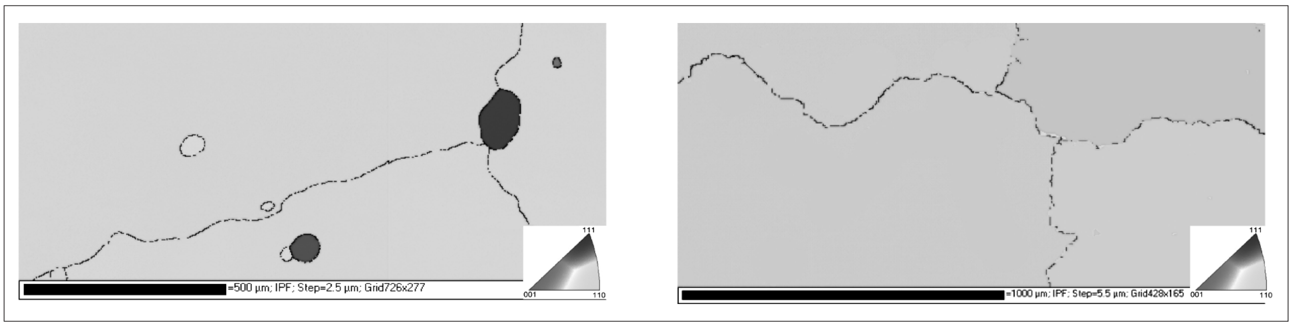


Figure 3. IPF maps representing secondary recrystallized state of a) G steel after laboratory annealing at 1025 °C for 5 min and b) FG steel taken after final industrial box annealing.

coarse-grained microstructure consisting from abnormally grown ferrite grains (see Figure 1c).

Increase of the annealing temperature up to 1100 °C leads to broken of selectivity conditions for abnormal grain growth see Figure 2. The broken of selectivity conditions reveals it self in pronounced growth not only particular grains but also the surrounding ones. Moreover, the grain growth character of particular grains is not so pronounced as in the previous case, cf. Figures 1c and 2. From the presented metallographic patterns, it is clearly evident that the application of short time annealing combined with dynamical heating of GO steel at particular temperature (~1025 °C) leads to abnormal grain growth development in the Fe-3 %Si.

IPF maps of the G and FG materials are shown in Figure 3a and b respectively. It is evident that in both case the developed huge grains possess Goss orientation. However, some parasitic grains are observed in G material annealed at laboratory conditions. The grains are "parasitic" because they have got unwanted from magnetic properties point of view {111} orientation, see Figure 3a. Moreover these small grains (~20 μm) are embedded into huge Goss grains. Small "parasitic" grains embedded in to huge Goss grains are not observed in the FG material treated under industrial conditions, see Figure 3b. The {100} pole figures representing texture state in G and FG materials are shown in Figure 4 and Figure 5 respectively. As one can see the sharpness of the developed huge Goss grains in both materials is similar, cf. Figures 4 and 5. Hence, texture state of Fe-3 %Si steel developed under dynamical heat treatment conditions is very close to that one developed under static industrial treatment. Process for elimination of parasitic grains presence needs further investigation. However the mentioned results obtained under the applied dynamical conditions are a good indication of possible application of continuous annealing for Fe-3Si steel production. Visions of the possible continuous annealing application instead of final box annealing of GO steels were discussed by Gunter et al. [5].

The onset of abnormal grain growth in the sample G occurs at 1000 °C, see Figure 1b. The map of grain boundaries distribution of the mentioned state is presented in Figure 6a. As one can see, the AGG proceeds in surrounding primary recrystallized matrix. It is clearly evident from the Figure 6a and b that most of grain boundaries between growing Goss grain and rests

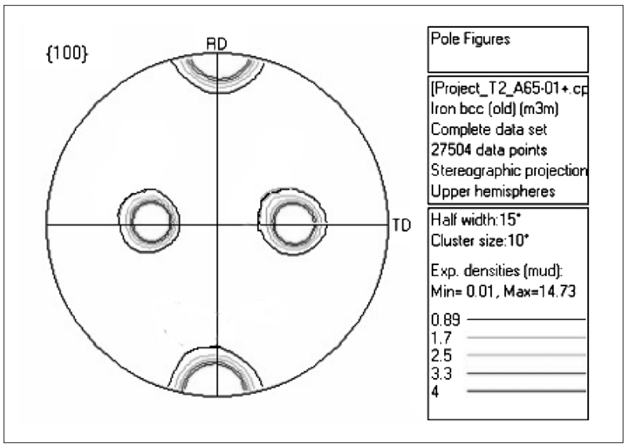


Figure 4. Pole figure representing texture state in G steel with abnormal grains annealed at 1025 °C for 5 min under laboratory conditions.

of the surrounding grains are HE boundaries. Moreover, the boundaries between parasitic grains and Goss one are also boundaries with misorientation in range of 40°-55°, see Figure 6a.

Concerning mechanism of Goss grains development under the applied dynamical heat treatment conditions, this mechanism arouses a big interest from scientific point of view. As was mentioned above, there are two principally different mechanism of Goss texture development. The both of mechanisms are based on the unique properties of boundaries of Goss grains. The first mechanism is coincident site lattice (CSL) mechanism ascribing high mobility to CSL boundaries. The second mechanism

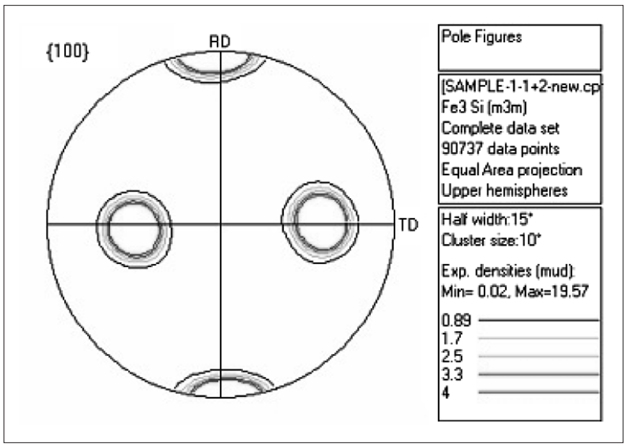
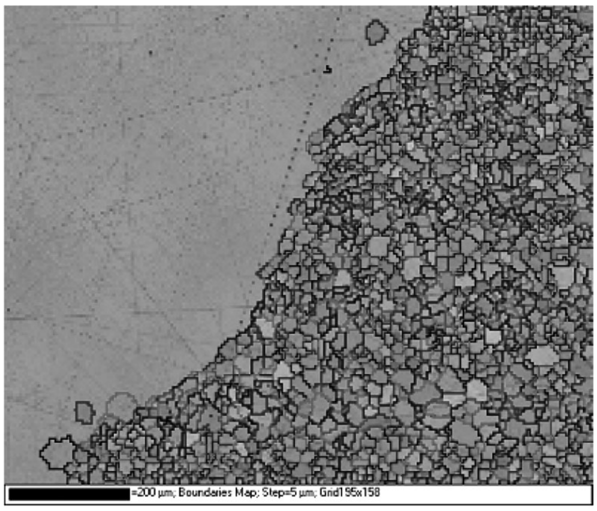


Figure 5. Pole figure representing texture state in FG steel annealed under industrial conditions.

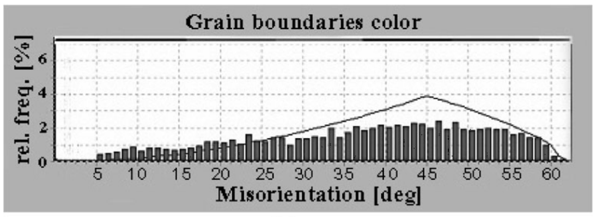
proposed by Szpunar et al. [4] assigns high mobility to high energy boundaries that mainly surround Goss grains. The idea here is that, the HE boundaries are characterized by high diffusivity that leads to quick coarsening or dissolution of precipitates during box annealing. The resulting large or missing particles have a lower pinning force on the moving boundaries than small particles on the other boundaries. However, none of the theories can give the explicit explanation of the AGG phenomenon. Moreover, each of the theories is based on the static method of the annealing for AGG development in the GO steel (box annealing). Hence, a self evident question erases from the results presented in the current work: whether the same mechanism of abnormal grain growth takes place under both static and dynamic conditions? The possible answer could be the following thoughts. As was concluded in Ref [6], the Goss nuclei are located in regions with low stored strain energy. Therefore, Goss grains could be faster recovered from dislocation than ones with other orientations [7]. Moreover, Inagaki observed fast both recovery and recrystallization in {110} deformed grains, while in {100} and {112} deformed grains these processes proceed very slowly [8]. The analogy could be drawn to the AGG development under dynamical conditions. That is, dislocations or boundaries in Goss grains possess (110) crystallographic planes can escape from the retarding pressure of secondary-phase particles first at particular temperature. Moreover, the observed high energy grain boundaries around the growing Goss grains are more capable to emit or capture dislocations [9]. It means that the Goss oriented grains gain an advantage of grain growth over the other grains and start to growth first. However, the process of secondary recrystallization under dynamic conditions is very sensitive on temperature. This is because the temperature has a direct impact on the grain boundary energy and mobility [10]. The elevated temperature has to be sufficient to initiate the growth of the Goss grains while the mobility of the rest orientations should approach zero. As was already shown the AGG takes place at particular temperature ~ 1025 °C. The application of somewhat lower or higher temperatures leads either to incomplete AGG or upset the selectivity conditions for the AGG. Therefore, the appropriative temperature for dynamic heat treatment has to be strictly controlled during the secondary recrystallization process. Anyway, the nature of abnormal grain growth under dynamic conditions is not understood enough and need further detailed investigation.

CONCLUSIONS

The secondary recrystallization phenomenon was investigated in the GO steel annealed under dynamical conditions. It was shown that in the investigated GO steel abnormal grain growth takes place at particular temperature. The developed under dynamical heat treatment conditions Goss grains have similar sharpness as that ones obtained after final box annealing in industry. The development of the AGG growth under dynamical heat treatment conditions is a good indication of possible application of continuous annealing for Fe-3 %Si steel production.



a)



b)

Figure 6. Map of grain boundaries distribution (a) and misorientation distribution with appropriative color key for the map (b) in G steel with microstructure representing start of abnormal grain growth.

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