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Hot Deformability of Si-Steel Strips Containing Al

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***Abstract*—**The present work is dealing with 2% Si-steel alloy. The alloy contains 0.05% C as well as 0.85% Al. The alloy under investigation would be used for electrical transformation purposes. A heating (expansion) - cooling (contraction) dilation investigation was executed to detect the α, α+γ, and γ transformation temperatures at the inflection points of the dilation curve. On heating, primary α was detected at a temperature range between room temperature and 687 °C. The domain of α+γ was detected in the range between 687 °C and 746 °C. γ phase exists in the closed γ region at the range between 746 °C and 1043 °C. The domain of α phase appears again at a temperature range between 1043 and 1105 °C, and followed by secondary α at temperature higher than 1105 °C. A physical simulation of thermo-mechanical processing on the as-cast alloy was carried out. The simulation process took into consideration the hot flat rolling pilot plant parameters. The process was executed on the thermo-mechanical simulator (Gleeble 3500). The process was designed to include seven consecutive passes. The 1st pass represents the roughing stage, while the remaining six passes represent finish rolling stage. The whole process was executed at the temperature range from 1100 °C to 900 °C. The amount of strain starts with 23.5% at the roughing pass and decreases continuously to reach 7.5 % at the last finishing pass. The flow curve of the alloy can be abstracted from the stress-strain curves representing simulated passes. It shows alloy hardening from a pass to the other up to pass no. 6, as a result of decreasing the deformation temperature and increasing of cumulative strain. After pass no. 6, the deformation process enhances the dynamic recrystallization phenomena to appear, where the z-parameter would be high.

***Keywords*—**Si-steel, hot deformability, critical transformation temperature, physical simulation, thermo-mechanical processing, flow curve, dynamic softening

I. Introduction

SILICON steel sheets are widely used as a core material for electrical machines such as motors, transformers, and generators. They should meet the requirements of low core loss and high magnetic induction in order to reduce energy losses and to enhance the efficiency during the process of electromagnetic transition. The magnetic properties are mainly influenced by steel cleanliness level, strip thickness, silicon concentration, grain size, as well as crystallographic texture [1], [2]. With respect to the effects of chemical composition, silicon is the prime interest of the whole alloying elements. Silicon in flat rolled electrical steels has an effect upon both eddy currents loss and hysteresis loss; increasing silicon content increases the volume resistivity of the steel, and thereby reduces the eddy currents loss. The hysteresis component is also reduced as the silicon content is raised, where silicon reduces the magnetic reluctance and lessens the amount of energy expended in magnetizing the core [3]. Contrary, as the Si-content of flat-rolled electrical steel is increased, the mechanical properties of the steel may be adversely affected. Increasing silicon content raises the yield point, shear strength, and generally decreases elongation [4]. From the microstructure point of view, silicon in low carbon steel restricts the formation of gamma phase (γ) so that, in excess of 2.25% Si and with 0.01 to 0.02% C or less, the alloy is completely ferritic from room temperature to the melting point, i.e. silicon in low-carbon steel decreases the tendency of the steel for aging [5].

Aluminium plays a similar role like Si, but to a lesser degree. Al is believed to influence the core loss by grain coarsening, texture and/or by changing the amount and distribution of the impurities [6]. Sometimes Si-steel efficiency is expressed in terms of an equivalent Si ($Si_{equ.}$) content as stated in [7];

$$Si\ equ = Si + 2Al - 0.5Mn + 0.251P \qquad (1)$$

where compositions are expressed in mass %.

Phase transformations in Si-steel alloys play an important role in construction of the hot rolling policy, which would lead to the exact dimensions of the sheets, as well as microstructure constituents, which are favoring the preferred grain orientations on subsequent processing steps. The steel chemical composition influences the phase transformations of the Si-steel. High Si-steel hot rolled sheets usually have coarse grained microstructures, which would enhance shear band formation during subsequent cold rolling [7]. Al plays a similar role as Si on stabilizing the ferrite phase and opposing austenite formation. On the other hand, carbon increases the gamma phase (γ) constituent of Si steels and detrimentally affects the magnetic properties [7]. Gomes et al. [8] found that the magnetic properties of electrical Si-steels such as permeability and specific losses are correlated with the microstructure and crystallographic texture. The left-hand side of the Fe- Si binary diagram is demonstrated in reference [9]. The binary diagram presents a closed (γ) loop, which is surrounded by a bi-phase (γ+α) domain and followed by a completely ferritic region [9].

The thermo-mechanical simulation process consists of rough deformation stage at the high temperature ferrite (α) region. The final deformation stages were conducted in the bi-phase (α+γ) domain and finished at the closed (γ) region, i.e.

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mixed rolling scenario was executed.

On a study about the influence of deformation process on the improvement of non-oriented electrical Si steel, it was concluded that, for medium Si-alloys, a mixed rolling is the optimum [10], where considerable cube texture components {100} /<001> in the bulk of the material would be created. Hot deformation behaviour of alloys is usually characterized by the simultaneous occurrence of strain hardening and dynamic softening. Strain hardening is characterized by the multiplication of dislocation density and consequent increase in the internal stress level as the deformation progress. However, the dynamic softening mechanisms can be divided into recovery and recrystallization [11]. Dynamic recovery (DRv) takes place at any amount of deformation, but its contribution to softening is more intense at the early deformation stages. It is classically associated with bcc crystallographic structure and high stacking fault energy (SFE) materials, e.g. iron ferrite.

On the work published by Kang and Torizuka [12], it was concluded that dynamic recrystallization can be obtained by large strain deformation with a high strain rate. A dynamic recrystallization phenomenon is usually controlled by Zener-Holloman parameter (Z);

$$Z = \dot{\varepsilon}\, e^{(Q/RT)} \quad (2)$$

where Q is the activation energy for hot deformation of Si-steel. Q was calculated as a function of the steel chemical composition [13];

$$Q(J/mol) = 267000 - 2535{,}52(C\%) + 1010(Mn\%) + 33620.76(Si\%) + 35651.28(Mo\%) + 93680.52(Ti\%)^{0.5919} + 31673.46(V\%) + 70729.85(Nb\%)\hat{}(0.5649) \quad (3)$$

R is the gas constant (8.318 J/mol K), and $\dot{\varepsilon}$ is the strain rate (s^{-1}).

The grain size of ferrite that can be recrystallized dynamically (d) can be expected by;

$$d = AZ^{-0.16} \quad (4)$$

where A is a constant, i.e. ultra fine grains can be obtained for a large Z-parameter with an increase in the strain rate ($\dot{\varepsilon}$) even in a high deformation temperature range [12].

Most of the previous works were focusing on the cold rolling and heat treatment cycles and its effect on the upcoming magnetic properties. However, there is a gap of knowledge in hot rolling processing and its impact on the electrical and magnetic properties of the thin Si/Al strips.

II. Experimental Work

The Si-Al steel alloy under investigation was prepared by melting in a 100-kg induction melting furnace. The melt steel was cast as Y-blocks with effective ingot dimensions 35×200×300 mm. The chemical composition of the steel alloy is stated in Table I.

TABLE I
Chemical Composition of Si-Al Steel Alloy

Element	C	Si	Mn	P	S	Al
wt.%	0.0556	1.95	0.179	0.0216	0.0160	0.848

A heating (expansion)-cooling (contraction) dilation investigation has been executed on the alloy and it results in dilation curves for determination of the critical and allotropic transformation temperatures before carrying out controlled hot deformation. Inflection points on the dilation curve represent the critical transformation and allotropic temperatures.

Thermo-mechanical simulation process was carried out using thermo-mechanical simulator (Gleeble 3500) taking into consideration: the critical transformation temperatures, and number of passes and amount of thickness reduction/pass at the pilot plant. Table II demonstrates technological data of the deformation process at the pilot plant.

TABLE II
Technological Data Representing the Deformation Parameters at the Pilot Plant

Pass #	Roughing stand	Finishing stands					
	1st	2nd	3rd	4th	5th	6th	7th
Thickness before pass, h_1, mm	75	31	18.02	11.024	7.236	4.937	3.725
Thickness after pass, h_2, mm	31	18.02	11.024	7.236	4.937	3.725	3.016
Thickness Reduction/pass, %	58.7	41.87	38.8	34.4	31.8	24.5	19
Temperature, °C	1096	982	962	945	925	910	892

III. Results and Discussions

Dilation curves on heating and cooling of the Si-Al steel alloy are presented in Figs. 1 and 2. Inflections which are representing critical transformations are precisely determined. It can be noticed that the transformation temperatures on heating shifted toward higher values than the values on cooling.

The proposed thermo-mechanical simulation process was coinciding with the mixed rolling scenario [10], i.e. beginning with rough deformation stage in the range of high temperature α phase and followed by finish deformation steps at the bi-phase (α+γ) domain, and finally the last deformation steps are executed at the closed γ- region. Fig. 3 schematically presented the thermo-mechanical simulation process. The simulation process took into consideration the deformation parameters in the flat hot rolling pilot plant. The deformation temperatures, number of passes as well as the strain rate are the same in the simulation process and in the pilot plant.

However, the amount of thickness reductions per each pass was dimensioned by a factor of 0.4, due to limitations of the effective length of the simulation specimens.

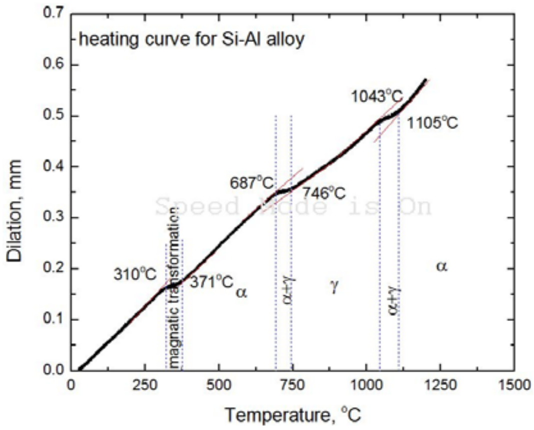

Fig. 1 Dilation curve for Si –Al steel alloy on heating

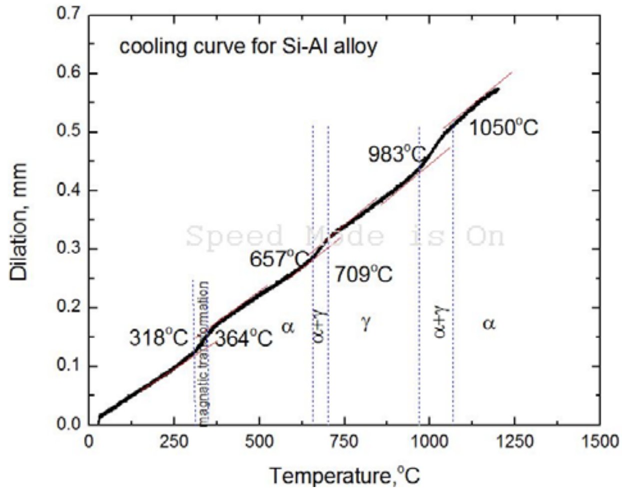

Fig. 2 Dilation curve for Si –Al steel alloy on cooling

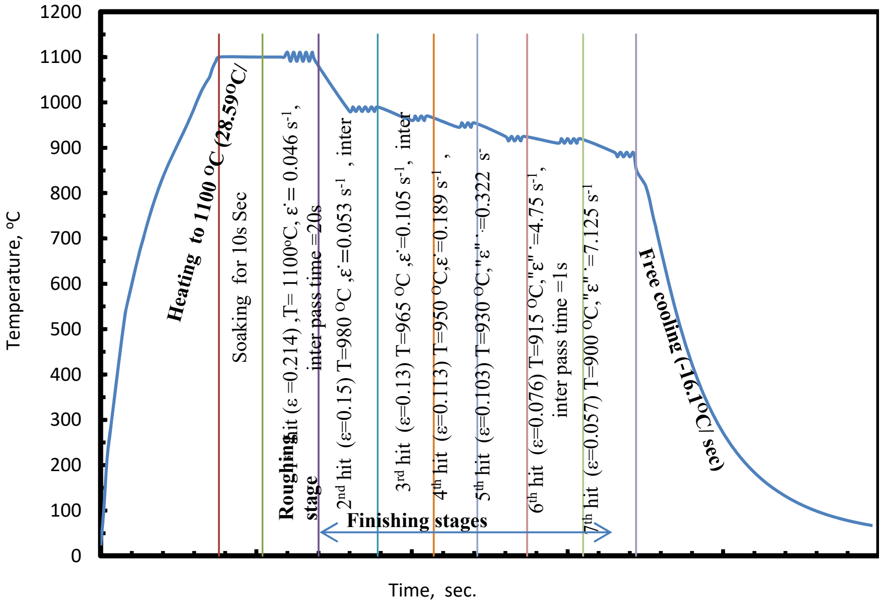

Fig. 3 Schematic presentation of seven consecutive deformation hits executed by the thermo-mechanical simulator (Gleeble 3500)

The interpass time after roughing was designed to be considerably higher than that after the finishing passes, to simulate the delay time between roughing and finishing stands in the pilot plant. The thermo-mechanical simulator (Gleeble 3500) generates stress- strain curve for each of the consecutive hits.

The multiple stress-strain curves obtained by the seven consecutive hits can be used to develop the flow stress of the Si- Al steel alloy. An envelope curve representing the different flow stresses is called flow curve. Fig. 4 shows the flow curve, which envelops seven consecutive stress- strain curves.

The continuous increase of the flow stress from a hit to another with the increase of accumulative amount of deformation, and fall of temperature is expected, due to the strain hardening effect. However, decrease of the flow stress after its continuous increase is argued to the creation of dynamic recrystallization, where temperature becomes lower and the strain rate is at its highest value, and consequently, the Zeiner Holleman parameter (Z) becomes very high. All these conditions would lead to the creation of dynamic recrystallization [13].

Variation of the Z-parameter from a hit to another is presented in Fig. 5. It is clearly shown that the Z-parameter increases continuously, where the strain rate ($\dot{\varepsilon}$) increases, while the hitting temperatures decreases. After hit no. 6, the Z-parameter highly increases, which would lead to ferrite grain refinement.

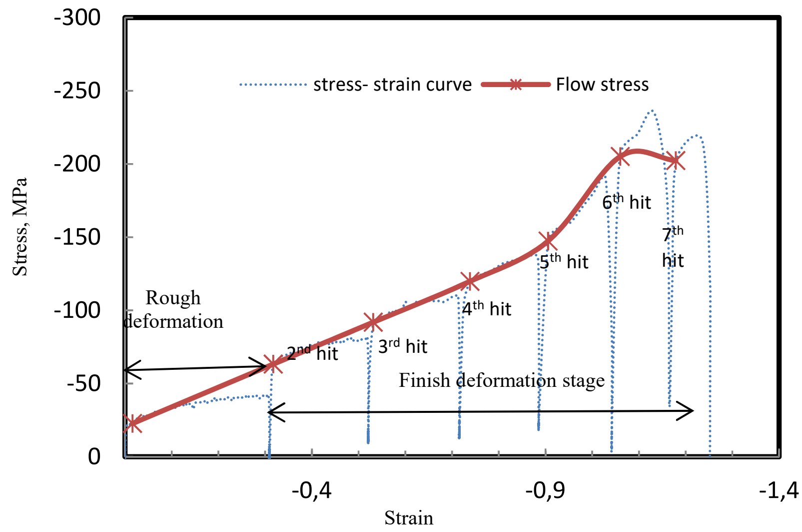

Fig. 4 Flow curve enveloping seven consecutive stress-strain curves

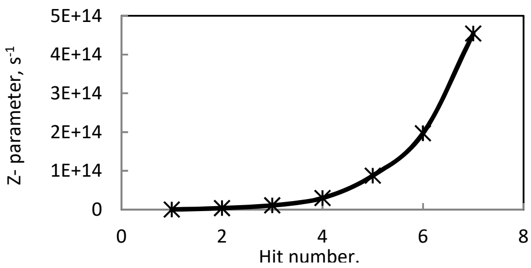

Fig. 5 Variation of Z-parameter with Hit number

Fig. 6 shows a microstructure of the thermo-mechanical simulation specimen by the “Gleeble 3500”, after subjecting to seven consecutive hits. The resulting microstructure obtained in Fig. 6 is due to two opposite effects;

- High Si and Al contents in the alloy, which is usually leading to ferrite grain coarsening.
- High Z-Parameter, which is leading to ferrite grain refining.

Consequently, the obtained microstructure contains two different grain sizes. Some ferrite grains were coarsened by the effect of Si and Al contents [6], while most grains were influenced by the effect of high z-parameter due to the hot deformation parameters of the last hit (no. 7) leading to dynamic recrystallization (grain refinement) [13]- [15].

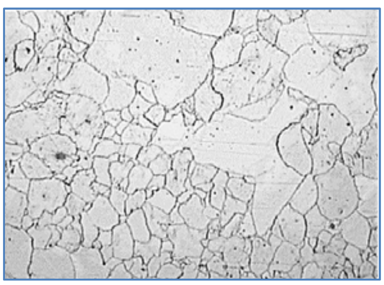

Fig. 6 Microstructure of high Si-Al steel of seven consecutive hits (X200)

IV Conclusion

- A beneficial multi –hit process was developed to simulation the thermomechanical processing of the Si –Al alloy
- The proposed deformation scenario results in dynamic softening, which would impact positively on the upcoming electrical and magnetic properties of the thin Si-Al strips.

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