# Softening behaviour at hot rolling of FeSi alloys with phase transformation

W. Müller, J. Schneider, W. Jungnickel, H. Hermann, and R. Kawalla

*The microstructure of hot rolled strips affects to a large extent the resulting microstructure of the cold rolled and finally annealed FeSi based electrical steels. In this paper the hardening and softening behaviour of FeSi alloys with phase transformation at hot rolling will be regarded. It will be pointed out that the present models describe the processes at hot rolling only in an incomplete way.*

KEYWORDS:
FeSi alloys, hot rolling, flow curves, softening behaviour, microstructure, nonoriented electrical steels

## INTRODUCTION

FeSi alloys with phase transformation are widely used as nonoriented electrical steels. The magnetic properties are influenced by metallurgical factors like the chemical composition and the processing parameters at reheating, hot rolling, cold rolling and annealing. The magnetic relevant microstructural features: grain size, relevant textures as well as the avoidance of precipitations are influenced by these metallurgical factors. The formation of preferred crystallographic orientations for optimum magnetic properties as well as an optimum grain size in the finally annealed material is remarkably affected by hot rolling conditions. It has been shown that hot strip annealing [1,2] as well as final hot rolling in the two phase region and ferritic region [3, 4] may result in better magnetization behaviour of the materials. The effect of the hot rolling conditions on the evolution of the microstructure, especially grain size and intensities of the magnetically relevant textures in FeSi alloys is not studied in detail.
In this connection it should be mentioned that the microstructural features of interest for electrical steels, by which the relevant magnetic properties are mainly determined, are partly different from those in the case of conventional steels as well as high strength steels. While the phase constitution and volume portion of different phases in the final rolled product are important for high strength steels, for the FeSi alloys with a Si-content up to about 1.8 wt.-%, the $\gamma/\alpha$ -phase transformation affects only the hot rolling process and the resulting microstructure in the ferritic hot rolled strips, which is finally cold rolled with a large deformation and annealed. While for the conventional and high strength steels a small grain size and a high intensity of the ({111}<uvw>) fibre is of interest in the finally annealed material, a low intensity of the ({111}<uvw>) fibre and a large grain size is desirable for the electrical steels. The main focus in the case of electrical steels is to evaluate the effect of processing steps: hot rolling, cold rolling and annealing on the resulting grain size and on the intensity of the relevant magnetic texture components: i.e. the {110}<001> Goss , {100}<001> cube and {100}<110> rotated cube and on the magnetically relevant texture fibres, i.e. the theta ({100}<uvw>) and eta ({hkl}<100>) fibre. It has been found that the grain size structure of the hot strip has a remarkable effect on the resulting texture in the cold rolled and annealed state [5]. For that reason a deeper understanding of the softening behaviour during and after hot rolling of FeSi alloys would be helpful to realize an optimum microstructure for the following processing steps of cold rolling and annealing. This will finally give also the basis for studying the interaction between the microstructure of the hot strip and the evolution of the microstructure during the following processing steps: cold rolling and annealing, on the microstructure and texture in the final product. At present there is no model, by which the evolution of the microstructure and texture along the processing route can be predicted.
The aim of this work is to get a data basis for modelling the hardening and softening. We will present in the paper the typical behaviour of the flow stress at hot rolling for the FeSi alloys with phase transformation. The various microstructures at different types of hot rolling will be demonstrated. The dynamic softening behaviour as well as the static softening behaviour is described in the austenitic and ferritic regions. Finally the results for modelling the softening behaviour at hot rolling are critically discussed.

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## EXPERIMENTAL

The starting materials are commercial FeSi alloys with phase transformation: FeSi steels with low Si-content of < 0.5 wt.-% and FeSi steels with medium Si-content in the range of 0.5 wt.-% to 1.6 wt.-%. As indicated in Fig. 1 all the regarded alloys exhibit a $\gamma/\alpha$ -phase transformation.
The flow curves were determined by compression tests for cylinders using a servohydraulic testing system. The maximum flow stress $\sigma_{max}$ is determined from the flow stress vs. strain curves. The critical strain $\varphi_c$ is found from the onset of dynamic recrystallization. For more details see [6].
The static softening behaviour was studied by two step upsetting tests using the Gleeble HDS-V40. The grain structure was investigated by optical microscopy. The grain size was determined using the linear interception technique. The homogeneity of the grain size and texture across the thickness, which is favourable for optimum magnetic properties, was also analyzed.
Hot rolling trials were realized using the four stand hot rolling pilot line.

## MODELLING THE SOFTENING BEHAVIOUR

The dynamic and static softening will be described by isothermal models, based on JMAK-theory [7-9].

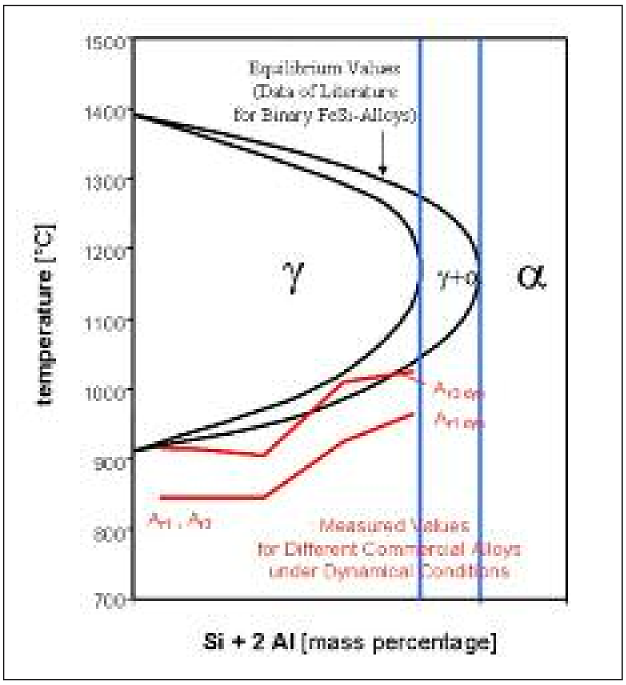


**FIG. 1** ***Correlation between Si-equivalent and temperature ranges for austenite and ferrite phases.***

*Correlazione fra Si-equivalente e intervalli di temperatura per le fasi austenite e ferrite .*

**Modelling of Dynamic Softening**

In the following we will use the nomenclature:
stress σ, temperature ϑ in °C, deformation φ, deformation rate $\dot\varphi = d\varphi/dt(s^{-1})$, activation energy $Q_i$
For $\varphi > \varphi_c$ ($\varphi_c$ critical deformation) there is dynamic recrystallization. One writes in this case:

$$\sigma_F(\varphi) = \sigma_{DRV}(\varphi) \qquad \text{for } \varphi < \varphi_c \tag{1}$$

with

$$\sigma_{DRV}(\varphi) = u\cdot\sqrt[n_2]{1-e^{-r\cdot\varphi^{n_1}}} \tag{2}$$

The function u and r are given by:

$$u = a_1\cdot D_0^{b_1}\cdot\dot\varphi^{c_1}\cdot e^{\frac{Q_1}{R\cdot\Theta}}, \tag{2a}$$

$$r = a_2\cdot D_0^{b_2}\cdot\dot\varphi^{c_2}\cdot e^{\frac{Q_2}{R\cdot\Theta}} \tag{2b}$$

with temperature Θ = ϑ + 273,15 in K. The starting grain size was not varied ($b_0 = b_1 = 0$).
The critical deformation $\varphi_c$ is given by:

$$\varphi_c = a_c\cdot\dot\varphi^{b_c}\cdot e^{\frac{Q_c}{R\cdot\Theta}}. \tag{3}$$

The recrystallized fraction is calculated according to the following equations:

$$X_{dyn}(\varphi) = \begin{cases} 0 & \text{for } \varphi \le \varphi_c \\ 1 - e^{-\ln 2\left(\frac{\varphi-\varphi_c}{\varphi_m-\varphi_c}\right)^2} & \text{for } \varphi > \varphi_c, \end{cases} \tag{3a}$$

with

$$\varphi_m = a_m\cdot\dot\varphi^{b_m}\cdot e^{\frac{Q_m}{R\cdot\Theta}}. \tag{3b}$$

$\varphi_m$ gives the deformation, where a fraction of 50 % is recrystallized. The effective flow stress is finally found by

$$\sigma_F(\varphi) = \sigma_{F0} + (1 - X_{dyn}(\varphi))\cdot\sigma_{DRV}(\varphi) + X_{dyn}(\varphi)\cdot\sigma_{DRX} \tag{4}$$

The effective flow stress is composed of three parts: $\sigma_{FO}$, $\sigma_{DRV}(\varphi)$, $\sigma_{DRX}$.
$\sigma_{FO}$ is given by:

$$\sigma_{F0} = a_0\cdot\dot\varphi^{b_0}\cdot e^{\frac{Q_0}{R\cdot\Theta}}. \tag{4a}$$

The contribution by dynamic recovery ($\varphi < \varphi_c$) is described by $\sigma_{DRV}(\varphi)$, see equation (2). The contribution due to dynamic recrystallization ($\varphi > \varphi_c$) is:

$$\sigma_{DRX} = a_3\cdot\dot\varphi^{c_3}\cdot e^{\frac{Q_3}{R\cdot\Theta}}. \tag{4b}$$

**Modelling of Static Softening**

The used equations are:

$$t_{0,5} = t_0 + (t_m - t_0)\cdot\sqrt[h_2]{h_1^{-1}\cdot\ln\left(\tfrac{1}{2}\right)} \tag{5}$$

with

$$t_m = g_1\cdot D_0^{g_2}\cdot\varphi^{g_3}\cdot\dot\varphi^{g_4}\cdot\exp\left(\frac{Q_{stat}}{R\cdot(\vartheta-\vartheta_B)}\right).$$

and the Ansatz:

$$X_{stat} = 1 - \exp\left(h_1\cdot\left(\frac{t_p-t_0}{t_m-t_0}\right)^{h_2}\right). \tag{6}$$

$t_{0,5}$ describes the time, where a fraction of 50 % is recrystallized. $\vartheta_B$ is a parameter and $t_p$ gives the time between forming steps. The initial grain size $D_0$ is determined experimentally.

**RESULTS AND DISCUSSIONS**

Fig. 2 gives typical flow curves for a FeSi alloy with low Si-content at various deformation velocities (deformation rate $\dot\varphi$: 0.1, 1, 10 $s^{-1}$).
Fig. 3 and 4 represent the calculated dynamic softening behaviour of the FeSi alloy with low Si-content at a rolling temperature of 700 °C (ferritic region) and 1200 °C (austenitic region). The model parameters were determined by a nonlinear numerical approximation method using the data of the experimental determined flow curves. The regarded range of the deformation parameter comprises;
φ = 0 ... 1.4 and $\dot\varphi$ = 0.1 ... 10 $s^{-1}$.
Fig. 5 and 6 show the calculated static softening behaviour of a FeSi alloy with medium Si-content in the ferritic and austenitic

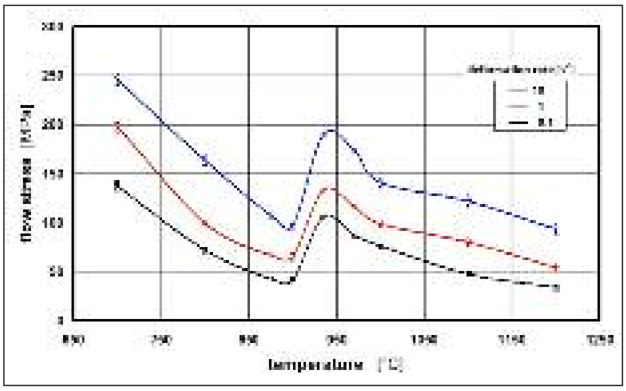

**FIG. 2** ***Flow curves for a FeSi alloy with low Si-content at various $\dot\varphi$.***

*Curve di flusso per una lega FeSi con basso contenuto di Si a diversi valori di $\dot\varphi$.*

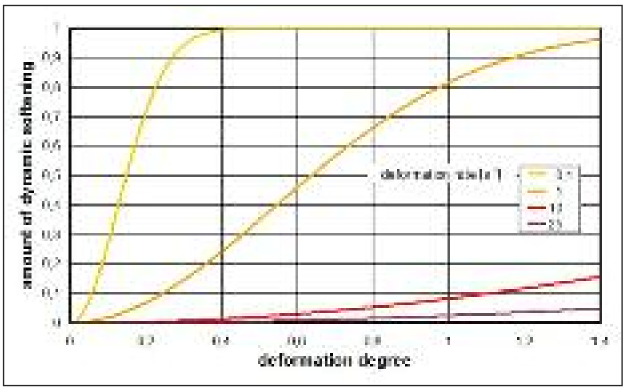


**FIG. 3** ***Calculated dynamic softening behaviour of the FeSi alloy with low Si-content at a rolling temperature of 700 °C (ferritic region).***

*Addolcimento dinamico calcolato di una lega di FeSi con basso contenuto di Si durante laminazione a una temperatura di 700 °C (regione ferritica).*

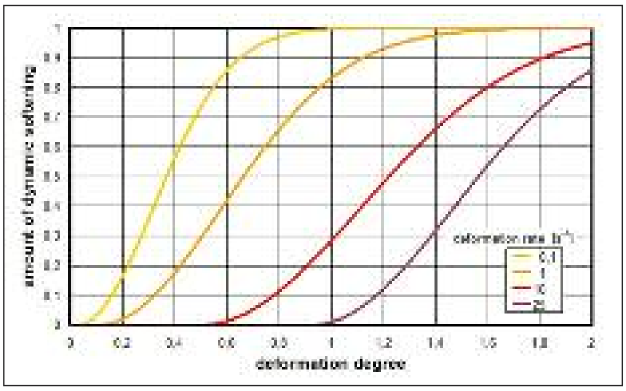


**FIG. 4** ***Calculated dynamic softening behaviour of the FeSi alloy with low Si-content at a rolling temperature of 1200 °C (austenitic region).***

*Addolcimento dinamico calcolato di una lega di FeSi con basso contenuto di Si durante laminazione a una temperatura di 1200 °C (regione austenitica).*

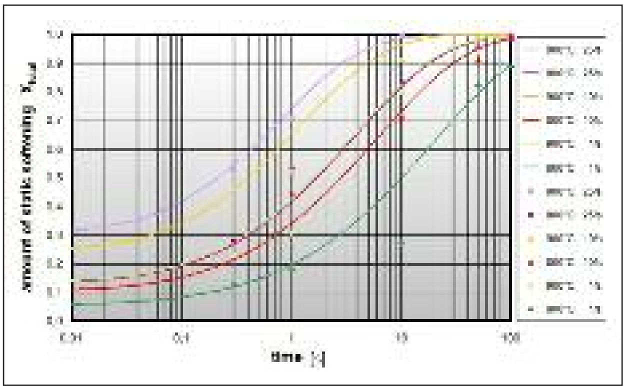


**FIG. 5** ***Calculated static softening behaviour of a FeSi alloy with medium Si-content in the ferritic temperature region.***

*Addolcimento statico calcolato di una lega di FeSi con medio contenuto di Si nella regione di temperatura ferritica.*

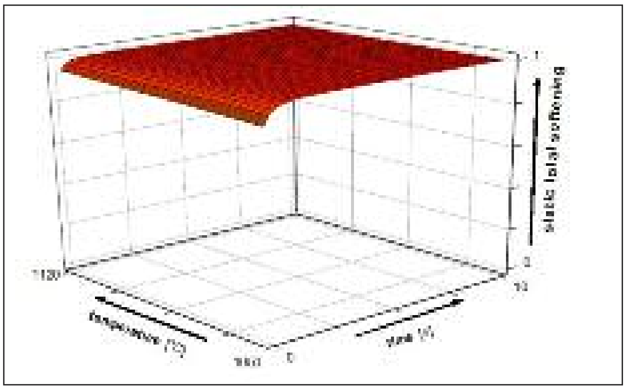


**FIG. 6** ***Calculated static softening behaviour of a FeSi alloy with medium Si-content in the austenitic temperature region.***

*Addolcimento statico calcolato di una lega di FeSi con medio contenuto di Si nella regione di temperatura austenitica.*

temperature region. The regarded range of the deformation parameter in this case comprises: $\vartheta$ = 800 ... 970 °C, $\dot{\varphi}$ = 1 ... 25 $s^{-1}$, $\varphi$ ~ 0.5 = const., $t_p$ = 0.1 ... 100 $s^{-1}$.
Fig. 7 gives the time $t_{0,5}$ for the appearance of 50 % of recrystallized volume.
The starting grain size $D_0$ was determined after reheating and cooling the samples to the regarded deformation temperature. However the static softening for these FeSi alloys with phase transformation depends on the "history of the samples". The thermally induced phase transformation during the time between two passes may affect the softening behaviour at hot rolling in the two phase region as well as in the ferritic region. Fig. 8 represents the different types of hot rolling, that may be realized for these alloys. Two phase rolling and mixed rolling result in improved magnetizing behaviour, see patents: EP 1056890, EP1192287, and EP 1194599. The different types of hot rolling give quite different microstructure in the hot strip, as demonstrated in Fig. 9 for a FeSi alloy with low Si-content.
The model of static softening in the ferritic region, which is described above, does not take into account the effects of the phase transformation as well as the existing mixture of ferritic and austenitic phases. It is necessary to improve the models for de-

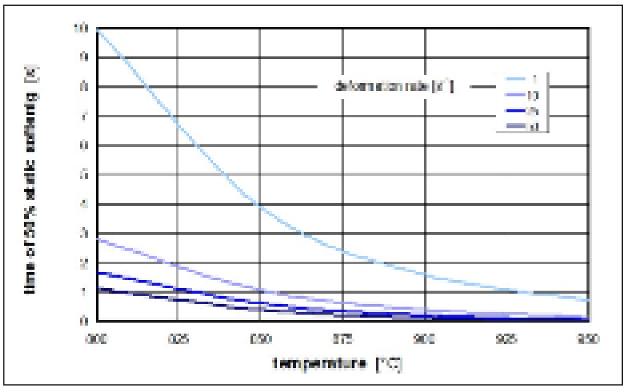


**FIG. 7** ***Time $t_{0,5}$ for the appearance of 50 % of recrystallized volume for the FeSi alloy with medium Si-content at various values of $\dot{\varphi}$.***

*Tempo $t_{0,5}$ per la comparsa del 50 % di volume ricristallizzato per la lega di FeSi con un contenuto medio di Si a diversi valori di $\dot{\varphi}$.*

scribing the softening behaviour taking into account the kinetics of the phase transformation as well as the effect of the existing mixture of the austenitic and ferritic phases on the deformation behaviour.

## CONCLUSIONS

The data obtained for FeSi alloys with phase transformation indicate rather fast micro structural changes at softening especially in the austenitic region. A separation in recovery and recrystallization demands more detailed investigations using EBSD tests.

The softening behaviour at hot rolling in the two phase region could not be described using the phenomenological models for the austenitic and ferritic regions. A more specified model description of the softening at final hot rolling by different passes has to take into account the resulting grain size before each of the passes. In the case that some of the passes are realized in the two phase region the model of softening in the ferritic region, at least the static softening, should take into account the kinetics of the phase transformation as well as the existing mixture of austenitic and ferritic phases.

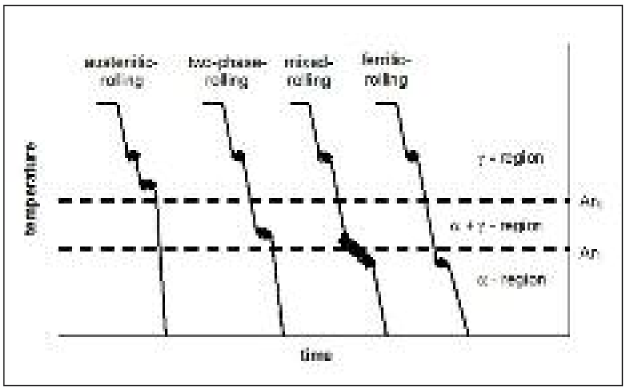


**FIG. 8** ***Different hot rolling technologies for FeSi-alloys with phase transformation.***

*Differenti tecnologie di laminazione a caldo per leghe FeSi con trasformazione di fase.*

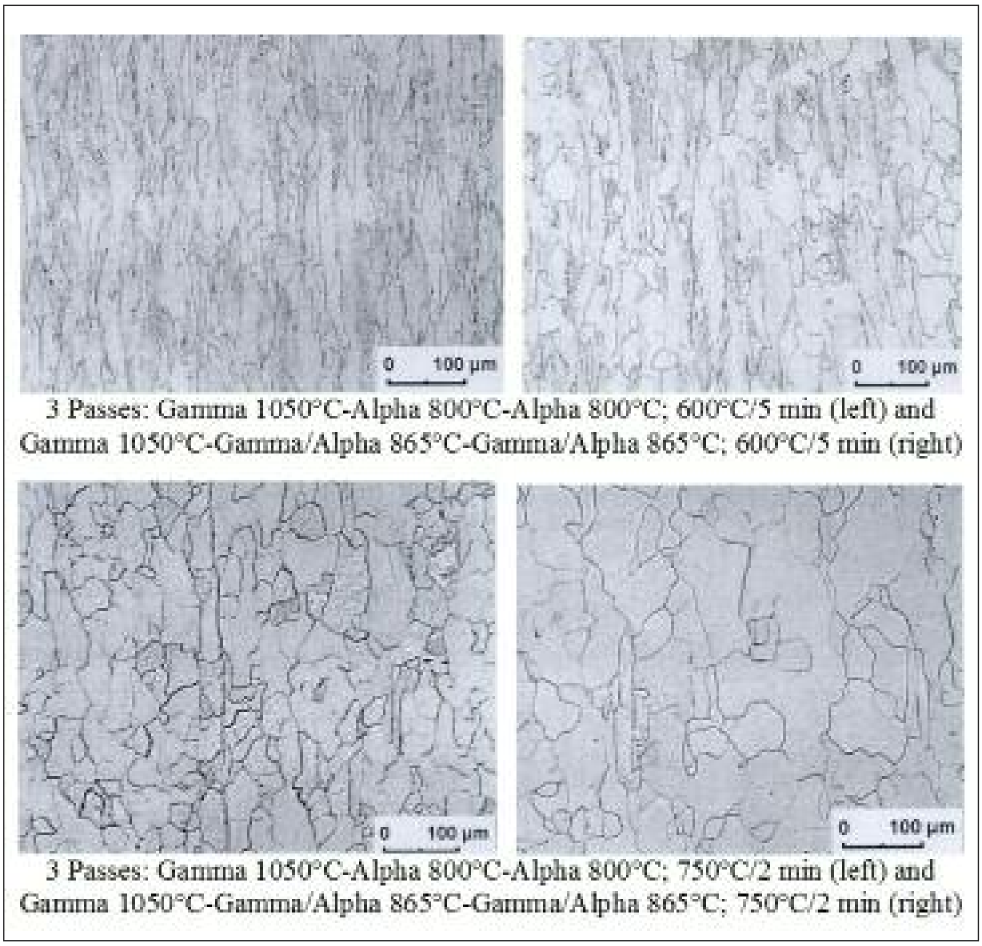


**FIG. 9**

***Grain structure after different hot rolling and treatments for a FeSi alloy with low Si-content: effects from hot rolling in different phases and from different cooling temperatures.***

*Struttura dei grani dopo differenti laminazioni a caldo e trattamenti per una lega FeSi a basso contenuto di Si: effetti della laminazione a caldo in diverse fasi e delle diverse temperature di raffreddamento.*

The dynamic as well as the static softening behaviour exhibit a rather complex dependence on the processing parameters: temperature, deformation degree $\varphi$, deformation rate $\dot{\varphi}$, time between the different passes $t_p$, starting grain size before starting deformation, alloy composition for the FeSi alloys with phase transformation. This allows by changing the parameter at deformation for the different passes at hot rolling to reach the optimum microstructure for the following processing steps of cold rolling and annealing.

In this respect, it is also necessary to take into account the changes in the microstructure due to the type of cooling from the finishing temperature at hot rolling to the coiling temperature as well as the changes in the microstructure at an additional hot strip annealing in the ferritic or in the two phase region. This additional processing step, hot strip annealing, is partly done to reach improved magnetization behaviour. To find the optimum microstructure of the hot strip, with respect to the optimum processing parameters at hot rolling, the role of the intensities of small angle as well as large angle grain boundaries within the hot strip on the resulting grain structure and texture after cold rolling and annealing has to be studied in addition.

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## Abstract

## Addolcimento durante la laminazione a caldo di leghe FeSi con trasformazione di fase

**Parole chiave:** acciaio e leghe, lavorazioni plastiche, trasformazioni di fase, modellazione

La microstruttura dei nastri laminati a caldo incide notevolmente sulla microstruttura degli acciai per usi elettrici a base di FeSi laminati a freddo e ricotti. In questo lavoro vengono esaminati il comportamento all'incrudimento e all'addolcimento delle leghe FeSi con trasformazione di fase durante la laminazione a caldo. Si sottolinea che i modelli riportati descrivono i processi durante la laminazione a caldo in modo incompleto.