Acta Materialia 96 (2015) 410–419

Contents lists available at ScienceDirect

Acta Materialia

journal homepage: www.elsevier.com/locate/actamat

Warm deformation and annealing behaviour of iron–silicon–(carbon) steel sheets

Makoto Atake *,[1], Matthew Barnett, Bevis Hutchinson [2], Kohsaku Ushioda [3]

Institute for Frontier Materials, Deakin University, Pigdons Rd., Geelong, VIC 3217, Australia

ARTICLE INFO

Article history:
Received 10 April 2015
Revised 14 May 2015
Accepted 16 May 2015

Keywords:
Silicon steel
Warm rolling
Texture
Flow stress
Shear bands

ABSTRACT

Single pass warm rolling and compression experiments were carried out from ambient to 800 °C for ultra-low carbon (ULC) steel with ~100 ppm carbon and interstitial free (IF) steels, both with two levels of silicon. Subsequently, annealing was done in order to recrystallize the deformed specimens. The main purpose of this study was to understand the effects of rolling temperature and silicon on stress responses and textures. This study comprises two main themes: flow stress and strain rate sensitivity during compression and shear banding and textures in warm rolled specimens. The effects of deformation temperature on in-grain shear bands were different between ULC-Si and IF-Si steels. As in previous work with more conventional steels, in-grain shear bands in the IF grade had low sensitivity to rolling temperature, while those in the ULC grade depended significantly on the deformation temperature. However, the temperature profile of shear banding in the ULC grade was approximately 150 °C higher than in previous work. Deformation and recrystallisation textures for both IF and ULC grades depended on their rolling temperatures. The variation of both grain size and texture after annealing can be explained by the rise and fall of in-grain shear banding activity which is related to the strain rate sensitivity.

1. Introduction

The microstructure, textures and properties of sheet steels are of great consequence in modern industrial society and, as such, have been widely researched. Important properties include strength, ductility, formability and magnetic behaviour. The products are typically manufactured by a sequence of treatments involving hot and cold rolling followed by annealing. There are, however, some advantages in using an intermediate route of warm ferritic rolling [1] which can also give rise to interesting effects, especially in relation to the development of texture.

Probably the first systematic investigation of warm rolling of low carbon steel was that of Hancock and Roberts [2] who observed that the normal cold rolling texture of steel strengthened at elevated rolling temperatures around 700 °C but that after subsequent recrystallization, the {1 1 1}//ND components that are desired for deep-drawability became very much weaker. Ushioda et al. [3] also reported weakening of the {1 1 1}//ND annealing texture after warm rolling but at lower temperature rolling in the range where dynamic strain ageing (DSA) occurs. This was shown to be associated with the formation of intense shear bands during rolling. Somewhat similar behaviour was reported by Senuma et al. [4] who also noted, however, significant differences between low carbon (LC) steels and interstitial-free (IF) steels where the carbon and nitrogen are bound up by titanium or niobium as second phase particles. Considerable clarification of these phenomena was provided by Barnett and Jonas [5,6] in a detailed comparison between LC and IF steels. They showed that the behaviour is intimately connected with DSA, in that steels with no free carbon (and no or little DSA) respond broadly in the same way over the whole temperature range, deforming in a moderately heterogeneous manner involving the formation of weak 'in-grain shear bands'. These local disturbances in the microstructure are important sites for nucleation of recrystallised grains with the {1 1 1}//ND orientations during annealing. When interstitial carbon is present, however, changes occur which depend on the temperature of rolling. At lower temperatures around 200–300 °C, DSA results in negative strain rate sensitivity and deformation becomes strongly localised into severe shear bands. On subsequent annealing, these bands occasion nucleation of Goss oriented grains as also shown previously [3].

* Corresponding author.
E-mail addresses: atake.f4g.makoto@jp.nssmc.com (M. Atake), matthew.barnett@deakin.edu.au (M. Barnett), bevis.hutchinson@swerea.se (B. Hutchinson), ushioda.cd8.kohsaku@jp.nssmc.com (K. Ushioda).
[1] Visiting from Nippon Steel & Sumitomo Metal Corporation, Yawata, Japan.
[2] Visiting from SwereaKIMAB, PO Box 7047, SE-16407 Kista, Sweden.
[3] Nippon Steel & Sumitomo Metal Corporation, Futtsu, Japan.

http://dx.doi.org/10.1016/j.actamat.2015.05.018
1359-6454/

Table 1
Chemical compositions of the steels (wt.% or wt.ppm).

Steel	Si (%)	C (ppm)	Ti (ppm)	Mn (%)	Al (%)	N (ppm)	S (ppm)	P (ppm)
IF-2.5Si	2.49	10	270	0.21	<0.01	9	<5	20
ULC-2.5Si	2.54	74	<10	0.21	<0.01	13	<5	20
IF-3.5Si	3.43	11	280	0.21	<0.01	9	<5	20
ULC-3.5Si	3.44	101	<10	0.21	<0.01	13	<5	20

At higher temperatures around 700 °C, the rate sensitivity becomes markedly positive as carbon atoms are pulled along with the moving dislocations creating a sort of viscous drag. Deformation then becomes very homogeneous and the as-rolled texture sharpens, but these microstructures are then too uniform to generate nuclei of the {1 1 1}//ND orientations on annealing. Instead, strain induced boundary migration (SIBM) takes over as the nucleation mechanism [7] whereby low energy sites with orientations such as (1 0 0)–(2 1 1)[0 1 1] are preferred. The resulting texture is detrimental for sheet formability but may offer advantages for soft magnetic properties.

The influence of other alloy elements, in particular chromium (Cr), has also been examined. Barnett [8] found that low carbon steel containing 1.3%Cr (wt.% hereinafter %) behaved to some extent like IF steel in that the temperature range for the heterogeneous microstructure and texture formation was raised by about 200 degrees. Favourable {1 1 1}//ND textures could then be achieved in annealed sheets after warm rolling at around 600 °C. These observations were compatible with earlier work of Glen [9] who had reported that the presence of Cr in steel extended the range of DSA to higher temperatures, thus confirming the link between the texture effects and DSA. Some effect of lower Cr contents was shown for contents down to about 0.5%. Additions of Mn, P and B to steels with around 0.5% Cr have also been investigated [10–12] to see whether the beneficial effect of Cr could be enhanced. In fact, the results were mostly inconclusive and the desired {1 1 1}//ND textures were generally weakened following warm rolling and annealing in these cases. The deleterious influence of elements such as Mn and B is well established, e.g. [13], so these results may only be peripherally related to the warm rolling conditions. Silicon is a notable and beneficial element as an alloying element in steel for several reasons. There have been many researches into the crystallographic texture of steel containing silicon because of its impact on magnetic properties which are important for electrical steels. Steels containing Si have been studied extensively after hot and cold rolling and annealing but little or nothing is known about warm rolled electrical steel. The aim of the present research was, therefore, to understand the combined effects of Si and rolling temperature on the crystallographic texture of steels containing silicon.

2. Experimental procedure

2.1. Materials

Four steel ingots having different compositions shown in Table 1 were produced by vacuum melting. These included two levels of silicon, 2.5% and 3.5%, and two levels of carbon, described as ultra-low carbon (coded ULC, with 70–100 ppm C) and interstitial free (IF, with about 10 ppm C). Titanium was added in IF-2.5Si and IF-3.5Si steels at sufficient levels to combine all the carbon, nitrogen and sulphur as TiC, TiN and TiS.

These ingots were rough rolled and finish hot rolled to 10 mm plates which were then annealed at 1000 °C for 1 min to acquire a fully recrystallized condition. Additionally, the IF-2.5Si and IF-3.5Si were annealed again at 700 °C for 1 h with the intention of precipitating any remaining free carbon as TiC as fully as possible and so, in principle, making the steel matrix free from interstitially dissolved carbon. The initial microstructures resulting from the pre-processing were coarse and equiaxed with average grain sizes of ~340 μm for IF grades and ~280 μm for ULC grades.

2.2. Compression testing

Compression specimens machined as 10 mmφ × 10mmH cylinders were prepared for tests using a Servotest thermo mechanical treatment simulator (TMTS) in the temperature range from ambient to 800 °C. Total deformations of 60% height reduction were applied. Boron nitride was painted as a lubricant on the top and bottom faces of the specimens which were pre-heated in the furnace box of the TMTS for 10 min. These were deformed with an initial strain rate of 2 s^{-1} up to ~30% reduction for initial flow stress measurements. The rate was then increased to 20 s^{-1} and subsequently returned to 2 s^{-1} for the purpose of calculating strain rate sensitivities. Samples were cooled with an air blower for 20 s immediately after compression.

Stress responses during compression were acquired from the compression tests, a typical example is shown in Fig. 1. The stress at a true strain of 0.1 ($\sigma_{0.1}$) can be read graphically from the strain–stress curves as a measure of the steady-state flow stress. The strain rate sensitivity m was calculated using measured stresses and the following equation:

$$m = \frac{\ln(\sigma_{high}/\sigma_{low})}{\ln(\dot{\varepsilon}_{high}/\dot{\varepsilon}_{low})}$$

Flow stress values in this case can be read using the extrapolation lines both from right and left and, therefore, two different values for m can be obtained. The difference between these values of the calculated m is considered as a measure of the uncertainty in the result and is represented by error bars in the graphs of results. Continuous compression tests were also carried out with strain rates of 0.002 s^{-1}, 0.2 s^{-1} and 2 s^{-1}.

2.3. Rolling experiments

Bars 40 mmW × 150 mmL × 10mmH were prepared having a taper at one end for gripping in the rolls. Single pass warm rolling tests (~60% reduction) were carried out in the range of temperature from ambient to 800 °C. The laboratory mill had a maximum load of 200 ton, with 350 mm diameter rolls and a rotation speed 14.5 rpm. These conditions correspond to a strain rate during rolling of ~10 s^{-1}. Tallow was painted on the surfaces of both rolls as lubricant. Before rolling, the specimens were heated in a muffle furnace until the required temperature was confirmed using thermocouples. After rolling, the samples were air cooled to room temperature. Subsequently, parts of the warm rolled samples were annealed for 5 min at 850 °C in a tube furnace in order to fully recrystallize them for observing the structures and textures. In some cases, samples of the as-rolled sheet were heated briefly in a sharp temperature gradient so that changes in microstructure could be observed at all stages from deformed to recrystallised within the same specimen.

2.4. Metallography and texture measurements

Specimens were prepared from cross-sections of the sheets in the as-rolled and recrystallised conditions for optical and scanning electron microscopy using standard procedures of grinding, polishing and etching. Electron back-scattering diffraction (EBSD) was employed both for examinations of the microstructures and for texture measurement. A particular difficulty was experienced in