

DEVELOPMENT OF BANDED MICROSTRUCTURE IN 34CrNiMo6 STEEL

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In this paper the development of a banded microstructure in hot-rolled 34CrNiMo6 steel which consisted of bainitic and martensitic bands is explained. The chemical compositions of the bands were measured with energy dispersive x-ray spectroscopy (EDS), which showed that the martensitic bands contained more alloying elements (Mn, Cr, Mo, Si) than bainitic bands. By using Oberhoffer reagent, the segregations of phosphorus were also revealed. These phosphorus segregations coincided with the positive segregations of the alloying elements. The continuous cooling transformation (CCT) diagrams of steel were calculated. They confirmed the formation of martensite in positive segregations and the formation of bainite in negative segregations.

Key words: 34CrNiMo6 steel, metallography, banded microstructure, phosphorus, CCT diagram

INTRODUCTION

A banded microstructure is a microstructure which consists of alternating bands of quite different microstructural constituents aligned parallel to the rolling direction of steel products [1–3]. It can have a very negative effect on impact properties in both the longitudinal and transverse direction. If the banded microstructure also consists of martensite bands it is detrimental for machining and subsequent cold forming operations [2, 4, 5]. The main reason for the development of a banded microstructure lies in the chemical inhomogeneity of the austenite. Namely, during solidification the content of solute elements and impurities increases in the liquid around solidifying dendrites which leads to interdendritic segregations [2]. However, the presence of interdendritic segregations does not necessarily lead to the development of microstructural banding after rolling. It's occurrence also strongly depends on the austenite crystal grain size and especially on the cooling condition from the austenite region. Since the mechanical properties of steels are significantly dependable on their microstructure and defects in it, it is very important to understand the basic cause for the development of microstructural banding in order to take appropriate action to minimise its occurrence and deleterious effect, especially on the cold forming process.

EXPERIMENTAL PROCEDURE

The development of a banded microstructure was investigated in heat treatable low alloy steel 34CrNi-

Mo6 containing chromium, nickel and molybdenum. Typical applications are for structural use, where a good combination of tensile strength and toughness is necessary, e.g. shafts, gears, bolts etc. The chemical composition of the investigated steel is listed in Table 1. It was supplied in a hot rolled bar with a diameter of 50 mm. Hot rolling started at 1 200 °C and finished at 875 °C.

Table 1 **Chemical composition of 34CrNiMo6 steel / wt. %**

Element	C	Si	Mn	P	S	Cr
	0,35	0,29	0,59	0,012	0,017	1,54
Element	Mo	Ni	Al	Cu	Fe	
	0,22	1,52	0,021	0,19	Balance	

The samples for microstructure characterisation were cut from the hot rolled steel bar in such a way that the normal to the sample surface was parallel to the axis of the bar. The samples were metallographically prepared and etched with ferric chloride. However, to reveal phosphorus segregations the samples were etched with the Oberhoffer reagent [6]. Microstructure analyses were performed with light (LM) and scanning electron microscopes (SEM), respectively.

For the calculation of CCT diagrams a computer programme JMatPro 7.0 [7] was used. By using this programme the CCT diagrams for S355J2 steel with different chemical compositions were calculated. When doing the calculations a crystal grain size of 9 according to the ASTM E112-12 standard was taken into account.

RESULTS AND DISCUSSION

The microstructure analysis of 34CrNiMo6 steel etched with ferric chloride performed with a light microscope revealed a banded microstructure. It consisted of alternating bands of mostly bainite (dark) and mostly martensite (light), aligned parallel to the rolling direc-

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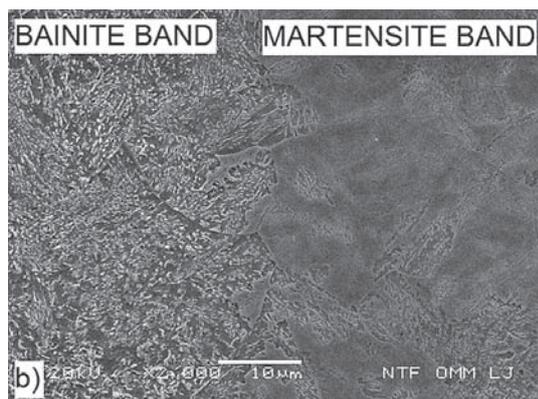
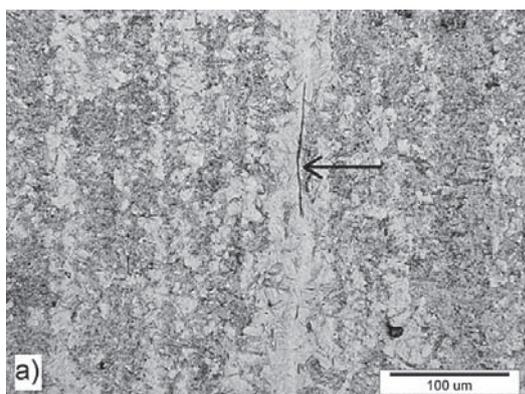


Figure 1 Banded microstructure in 34CrNiMo6 steel; a) light microscopy, b) SEM-SEI

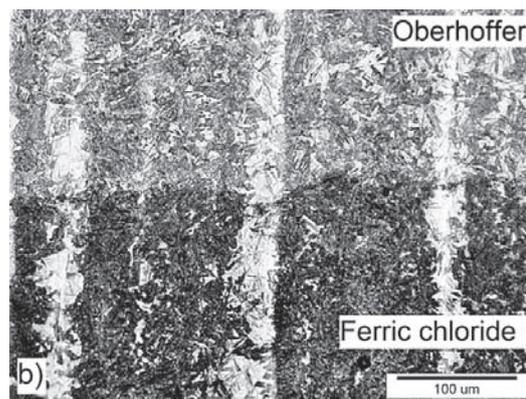
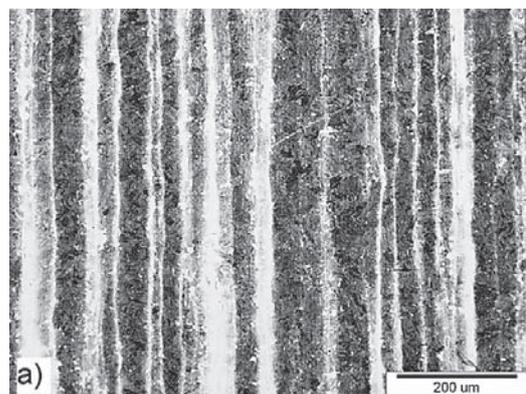


Figure 2 Phosphorus segregations; a) etched with Oberhoffer reagent (bright bands), b) etched with Oberhoffer reagent (upper part) and ferric chloride (bottom part)

tion of the bar (Figure 1a). However, the portion of martensitic bands increased with the distance from the edge of the bar towards the centre.

The microstructure observation (Figure 1a) showed that MnS inclusions (one marked with an arrow) were elongated and present in martensitic bands. Figure 1b shows the bainitic and martensitic bands at higher magnification. The microstructure of the same sample etched with the Oberhoffer reagent is shown in Figure 2a. This reagent revealed that the phosphorus segregations (bright areas) were very intensive. From Karl [8], the lower limit of phosphorus detection using the Oberhoffer reagent is 0,003 %. It can be seen that phosphorus was present in alternating bands, parallel to the rolling direction as well. Figure 2b shows the microstructure of the steel bar after etching with ferric chloride (bottom part of the sample) and Oberhoffer (upper part of the sample). It is clearly visible that phosphorus segregations coincide with martensitic bands.

A further EDS analysis was performed. The average results in the mostly bainitic and mostly martensitic bands (Figure 3) are presented in Table 2. They indicated that in mostly bainitic bands the content of alloying elements (Si, Cr, Mn, Ni and Mo) was lower (negative segregations) in comparison to the results of the nominal chemical composition of the investigated steel listed in Table 1, while in mostly martensitic bands, the content of these elements was higher (positive segrega-

tions). Note that the EDS analysis is not a proper method for the measurement of light elements (e.g. carbon) and elements with a concentration below 0,1 %. Since the concentration of phosphorus was below the detection limit of the EDS analysis it was not taken into account. However, it is well known that manganese lowers the activity of carbon in austenite and thus Mn-rich regions tend to attract carbon from neighbouring areas. Hence, in the Mn-rich regions, an increased concentration of carbon was expected. While chromium has a similar effect to that of manganese, phosphorus increases carbon activity and, as a result, rejects the carbon from the phosphorus-rich regions [9].

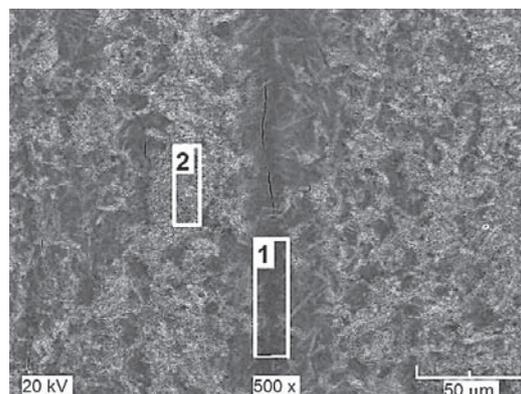


Figure 3 SEM micrograph of banded microstructure of 34CrNiMo6 steel marked with analysed regions

Table 2 Results of EDS analysis / wt. %

Element	Si	Cr	Mn	Ni	Mo	Cu	Fe
Site 1	0,37	1,92	0,67	1,68	0,61	0,32	Balance
Site 2	0,21	1,08	0,42	1,34	0,18	0,27	Balance

Regarding the activity of carbon, manganese and phosphorus have the opposite effect. Because the concentration of manganese and chromium in steels is much higher than that of phosphorus, manganese and chromium has a prevailing effect on the distribution of carbon in austenite. Therefore, it is assumed that regions that are rich in alloying elements (Mn, Cr, Mo) and phosphorus are also rich in carbon, despite the fact that phosphorus increases carbon activity. On the other hand, the austenite regions depleted in alloying elements and phosphorus contain less carbon.

The CCT diagram of the 34CrNiMo6 steel with the nominal chemical composition given in Table 1 is shown in Figure 4a. However, for comparison, CCT diagrams for the same steel with the chemical compositions measured with EDS in the positive segregations, i.e. in the mostly martensitic bands (4b) and negative segregations, i.e., in the mostly bainitic bands (4c), were also calculated.

The formation of banding in 34CrNiMo6 steel can be explained with calculated CCT diagrams. Namely, at a normal cooling rate of approximately 0,4 °C/min (bolded line in Fig. 4a) in steel with a nominal composition listed in Table 1 both martensite and bainite can be expected in the microstructure. However, the alloying elements (Mn, Cr, Mo, Si) have a strong effect on the hardenability since they move the CCT diagram to the right. Hence, in regions with an increased concentration of alloying elements (positive segregations) a critical cooling rate is achieved and thus only martensite can form (Figure 4b), while in regions with a lower concentration of alloying elements (negative segregations) mainly bainite is expected (Figure 4c).

In this calculation the changes in the concentration of carbon and phosphorus were not taken into account since they could not have been analysed with EDS. Anyway, it is known that both elements significantly increase the hardenability of steel since they move the CCT diagram further to the right, to a longer timing, and as such enable the formation of martensite. Phosphorus thus significantly enhances hardenability and can even cause both quench cracking and quench embrittlement [10, 11].

Since the concentration of alloying elements as well as phosphorus and carbon increases towards the centre of the ingots, the proportion of martensitic bands was higher towards the centre of the hot-rolled bar because the concentration of these elements in austenite regions was high enough for a critical cooling rate to be achieved. Also, the martensite start temperature (M_s) was slightly lowered with an increased concentration of alloying elements.

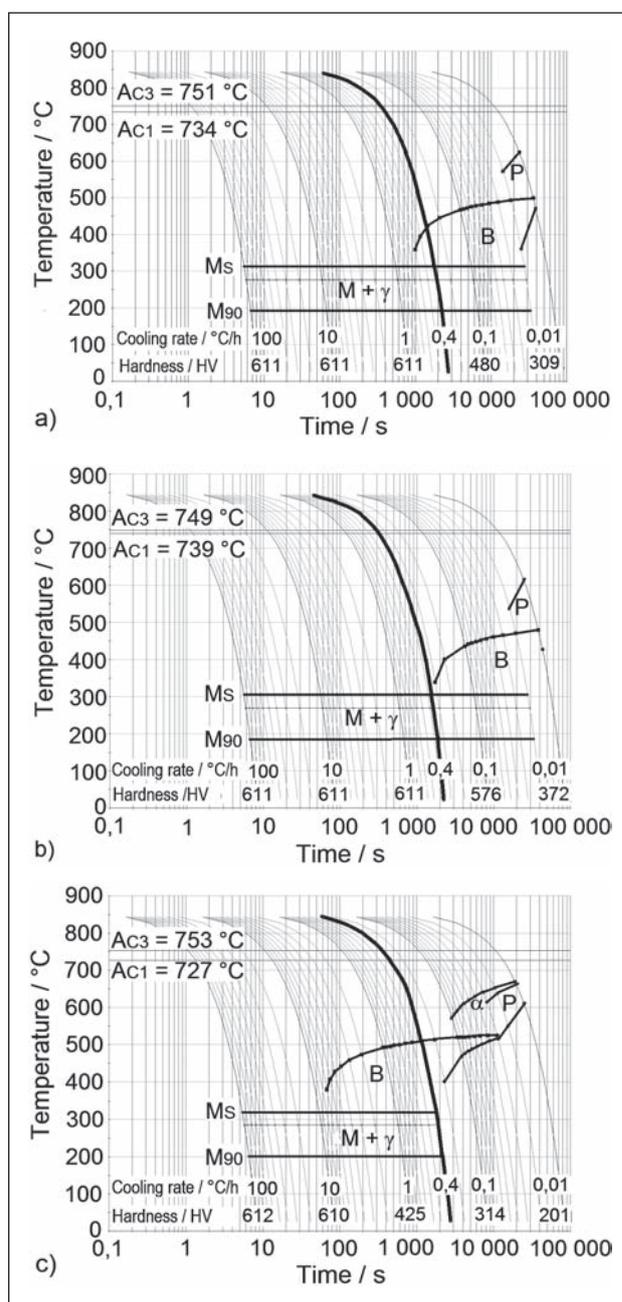


Figure 4 Calculated CCT diagrams for 34CrNiMo6 steel with a) the nominal chemical composition, b) with the composition in mostly martensitic bands (positive segregations) and c) with the composition in mostly bainitic bands (negative segregations)

CONCLUSIONS

A banded microstructure can be detrimental for machining and subsequent cold forming operations of steel. Thus, it is essential to understand the primary reasons for its development. In this paper the development of a banded microstructure consisting of mostly bainitic and mostly martensitic bands in hot-rolled 34CrNiMo6 steel was explained. The portion of mostly martensitic bands increased when moving from the edge of the bar towards the centre. The EDS analyses showed a higher concentration of alloying elements (Mn, Cr, Mo and Si) in the mostly martensitic bands in comparison to the mostly

bainitic bands. However, the EDS analyses did not show the presence of phosphorus because the quantity was below the detection limit of our EDS detector. Etching with the Oberhoffer reagent revealed bands of phosphorus segregations that coincided with positive segregations of alloying elements. The alloying elements (Mn, Cr, Mo, Si) have a strong effect on hardenability since they move the CCT diagram to the right. Phosphorus and carbon were not taken into account when calculating the CCT diagram, they could not have been analysed with EDS. However, they move the CCT diagram further to the right, to a higher timing, and as such enable the formation of martensite. Since the concentration of alloying elements as well as phosphorus and carbon increases towards the centre of the ingots, the proportion of martensitic bands was higher towards the centre.

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REFERENCES

- [1] B. Zorc, J. Bernetič, A. Nagode, Effects of Welding Residual Stresses and Phosphorus Segregation on Cleavage Delamination Fracture in Thick S355 J2 G3+N Steel Plate, *Engineering Failure Analysis* 40 (2014), 8-14.
- [2] G. Krauss, *STEELS Processing, Structure and Performance*, ASM International, Ohio (2005).
- [3] T. F. Majka, D. K. Matlock, G. Krauss, Development of microstructural banding in low alloy steel with Mn simulated segregation, *Metallurgical and Materials Transactions* 33A (2002), 1627-1637.
- [4] M. Muhič, F. Kosel, A. Pukšič, D. Klobčar, A new approach to monitoring thermal fatigue cracks in die casting moulds, *IJMR* 102 (2011) 1, 69-75.
- [5] G. Kosec, A. Nagode, I. Budak, A. Antić, B. Kosec, Failure of the pinion from the drive of a cement mill, *Engineering Failure Analysis* 18 (2011) 1, 450-454.
- [6] H. Schumann, *Metallographie*, VEB DVG, Leipzig (1987).
- [7] JMatPro 7.0, Sente Software Ltd., United Kingdom.
- [8] A. Karl, Investigations into the Suitability of the Oberhoffer Etch for Identifying Surface Defects, *Praktische Metallography* 15 (1978), 469-485.
- [9] G. Krauss, Solidification, segregation, and banding in carbon and alloy steels, *Metallurgical and Materials Transactions B* 34B (2003), 781-792.
- [10] G. Roberts, G. Krauss, R. Kennedy, *Tool Steels*, 5th Edition, ASM International, Ohio (1998).
- [11] F. A. Jacobs, G. Kraus, The Effects of Phosphorus and Carbon on the Hardenability of 41xx Type Steels, *Journal of Heat Treating* 2 (1981) 139-146.

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