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Influence of Strip Cooling Rate on Lüders Bands Appearance During Subsequent Cold Deformation

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Abstract. This paper presents the results of study of Lüders bands appearance on hot rolled strip during cold deformation. The research was carried out on niobium microalloyed steel. After the thermomechanical treatment the strip was cooled at different rates. Samples taken from hot rolled strip were tested by stretching to fracture with simultaneous application of the methods thermography and digital image correlation. The analysis of measurement results was performed with the software packages IRBIS 3 professional and MatchID. Significant differences were found in the samples tested at different cooling rates. In the samples cooled at a lower cooling rate, the appearance of Lüders bands in the elastoplastic area was determined. The appearance of Lüders bands was not observed in the samples cooled at a higher rates.

Keywords: Lüders band · Microalloyed steel · Hot rolled strip · Cooling rate

1 Introduction

In the last few years the occurrence and propagation of the Lüders bands [1, 2] have been intensively investigated. Lüders bands were observed and studied in the fifties of the last century and connected with retarding and accumulation of dislocations on obstacles [3, 4]. At that time it could not fully explain the mechanisms of Lüders bands formation and propagation. This phenomenon is again intensively investigated by the development of modern methods such as thermography and visioplasticity with digital image correlation (DIC) [5, 6]. The appearance of Lüders bands, Lüders bands propagation during deformation, and the stresses and deformations in, on and beyond the Lüders band front can be determined using thermography and digital image correlation simultaneously with a static tensile test [7].

Numerous studies of the Lüders bands occurrence and propagation have been carried out on various metal materials under different test conditions [8–10]. The influence of strain rate [9, 10], microstructure and dislocation density [3, 8] is studied. However, there is still no generally accepted conclusion of the cause of the Lüders bands formation and which factors influencing Lüders bands formation and propagation through the deformation zone.

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In this paper are presented the results of research of Lüders bands appearance using thermography and digital image correlation (DIC) on niobium microalloyed steel. The studies were carried out on hot-rolled strip which is cooled at a different cooling rates after thermomechanical treatment.

2 Experimental

Studies were carried out on microalloyed steel with 0.035% Nb. Chemical composition of steel is given in Table 1. Strip with thickness of 3 mm is rolled from steel. Rolling parameters of strip have shown in Table 2. After the thermomechanical treatment, Table 2, the strip was air-cooled (A) and water-cooled up to 510 °C and then air-cooled (B). The measurements were performed by contact platinum-rhodium pyrometry. Measured values have shown in Table 3.

Table 1. Chemical composition of steels [wt.%]

	C	Mn	Si	Al	S	P	Nb	N
%	0.09	0.75	0.05	0.020	0.014	0.018	0.035	0.0081

Table 2. Rolling parameters of strip 50 × 3.0 mm

Rolling parameters	Number of rolls						
	1	2	3	4	5	6	7
T deformation, °C	990	968	947	942	912	858	820
h_0, mm	20.20	17.11	13.28	10.10	7.05	5.28	3.70
h_x, mm	17.11	13.28	10.10	7.05	5.28	3.70	3.04
Reduction in the roll Δh, mm	3.09	3.63	3.18	3.05	1.77	1.58	0.66
Total reduction ε, %	15.30	34.26	50.00	65.10	73.39	81.86	84.95

Table 3. Cooling of strip

Cooling time, s		0	10	25	35	50
Temperature, °C	A	820		690	650	520
	B	820	680	510	–	–

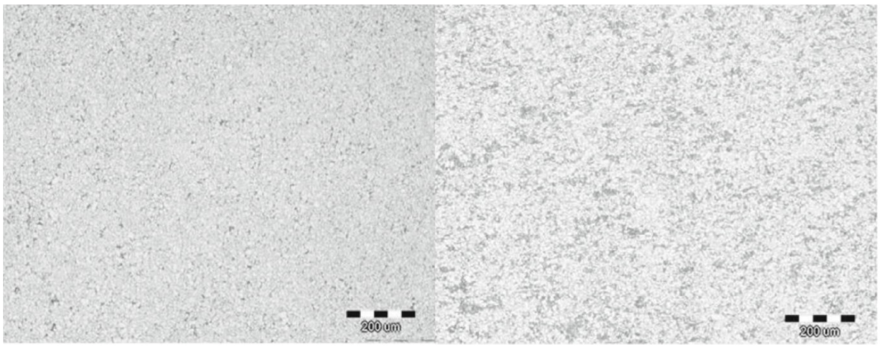
After cooling, samples were taken for structural testing. The samples were prepared for metallography and tested on the Olympus DP70 optical microscope.

Research of the Lüders bands occurrence and propagation was carried out by stretching to the fracture on the static tensile machine EU 40mod 400 kN, at stretching rate of 20 mm/min (strain rate 0.007 s^{-1}). The tests were performed simultaneously with thermography and digital image correlation (DIC). Samples were prepared by grinding the oxide layer and applying a black matte coating with emissivity factor of

0.95. White speckle patterns were applied on the black background for digital image correlation (DIC). Samples were recorded with infrared camera VarioCAM M82910 with temperature sensitivity of 80 mK and digital camera Panasonic HDC-SD9 with 2.1 MP resolution. The results of thermographic measurements were analyzed by Irbis professional software package and digital image correlation measurements were analyzed with MatchID software package.

3 Results and Discussion

The results of the metallographic tests are shown in Fig. 1. The both samples from strip have a fine-grained ferrite-pearlite microstructure. The strip cooled at a lower average cooling rate, sample A (average 6 °C/s), Fig. 2A, has a homogeneous fine-grained microstructure. Grain size is below 10 µm. Sample B, the strip cooled at a higher average cooling rate (average 12.4 °C/s), has a microstructure with a slightly higher percentage of pearlite. Grain size is 10–20 µm.



sample A sample B

Fig. 1. The microstructure of strip with: (A) average cooling rate 6 °C/s, (B) average cooling rate 12.4 °C/s

It is well-known that niobium microalloyed steels have a fine-grained ferrite-pearlite microstructure which is a consequence of the performed thermomechanical treatment. In the final phase of thermomechanical treatment, niobium precipitates are excreted, which have a strong influence on recrystallization. After the phase transformation a fine-grained microstructure is obtained as in Fig. 1 because of the high density of dislocation. The cooling rate has a significant effect on the grain size. At this stage of thermomechanical treatment $\gamma \rightarrow \alpha$ phase transformation takes place. As the cooling rate is higher, the greater proportion of carbide phases is in the structure.

The mechanical properties of the strip were examined. The obtained results are shown in Table 4. As expected, sample B has a higher tensile strength and hardness but lower elongation. It was found during mechanical properties testing that in homogeneous, fine-grained microstructure of sample A, inhomogeneous deformations occur at the start of plastic material flow, Fig. 3. Sample B do not have pronounced yield strength.

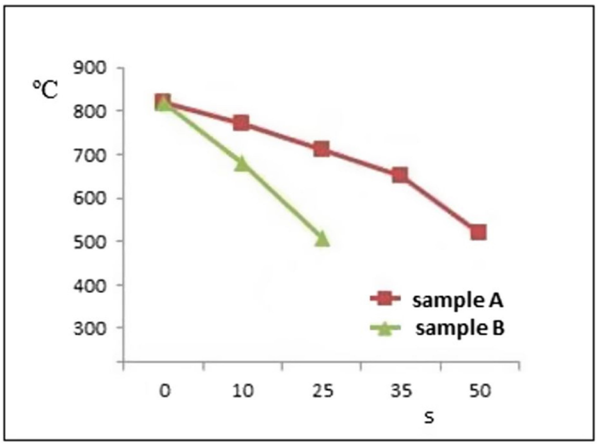


Fig. 2. Cooling rate of strip

Table 4. Mechanical properties of the strip

	R_p, MPa	R_m, MPa	A_5, %	HB
A	436	505	32.2	160
B	457	621	18.9	218

Inhomogeneous deformations in the sample A are associated with the occurrence of the Lüders bands [6], which was confirmed by thermography and digital image correlation on Figs. 4 and 5.

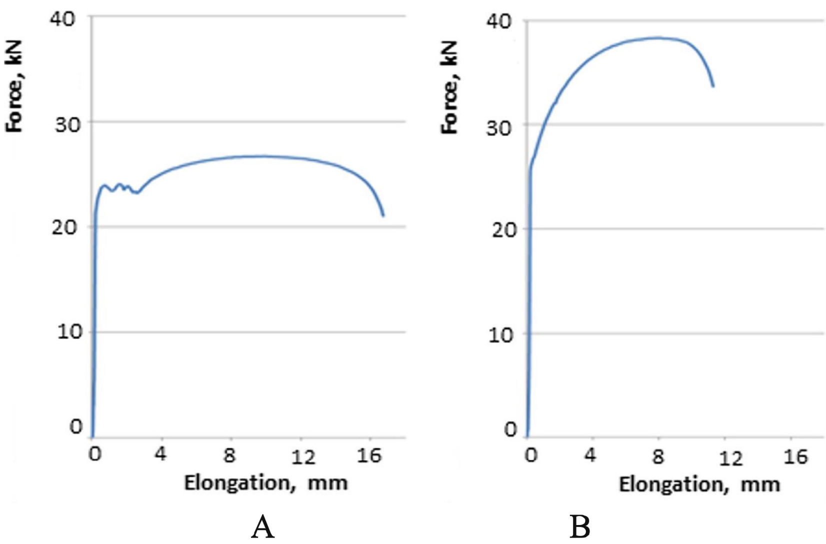


Fig. 3. Force-elongation diagrams

The captured thermograms, Fig. 4, show that in the sample A with inhomogeneous deformation, Fig. 3, Lüders band occurs. After reaching R_p, Lüders band formation begins at one end of the sample. From the point R_p to the start of inhomogeneous deformations, the Lüders band is formed at an angle approximately equal to the angle 45°.

After that, the Lüders band propagates through the deformation zone to the other end of the deformation zone. In this area inhomogeneous deformations are visible on the force-elongation diagram. There are no temperature changes in front of the Lüders band front. In this field elastic deformation takes place. Behind the Lüders front, there is a certain temperature increase that increases as Lüders band propagates through the deformation zone. This is associated with redistribution of dislocations. In sample B, with no pronounced yield strength, there are no Lüders bands. Stresses are concentrated in the middle of the sample and spreads through the deformation zone.

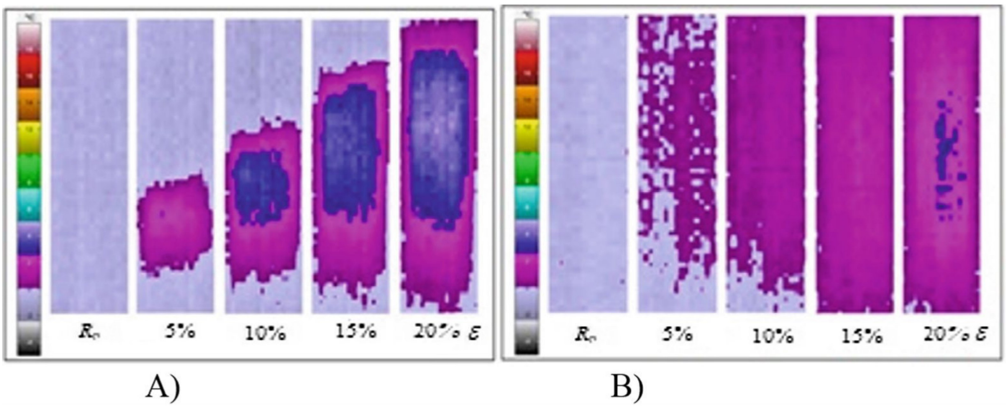


Fig. 4. Thermograms at the start of plastic flow of material

The results obtained by thermographic analysis were also confirmed with digital image correlation (DIC), Fig. 5. On the sample A, the occurrence and propagation of the Lüders band was observed while on the sample B, Lüders band was not observed. By comparing the recorded maps, Fig. 5, it can be seen that increasing of total deformation increases the amount of deformation behind the Lüders band front. Sample B shows considerably lower deformation amounts than sample A.

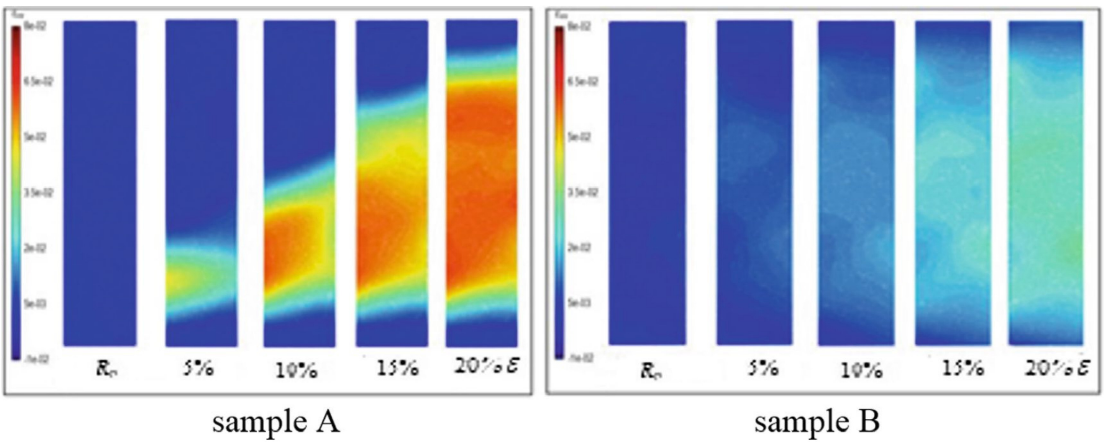


Fig. 5. Deformation maps at the start of plastic flow of material

The results of the recent research [7] of niobium micro-alloyed steel behaviours during cold deformation show that Lüders bands do not occur in inhomogeneous ferrite-pearlite microstructures with a significant difference in grain size. Comparing the microstructure of Fig. 1 with the research in [11], it results that the microstructure is not a reason for the different behaviour of samples A and B at the start of the plastic material flow. It can be concluded from Table 4 that the internal stresses in sample B are higher due to higher cooling rate. This indicates higher density of less mobile dislocations. In niobium micro-alloyed steels at the end of thermomechanical treatment are excreted deformation induced precipitates that interact with dislocations [2]. It is a realistic assumption that the different behaviour of samples A and B at the start of the plastic flow is related to the dislocations that interact with the precipitates, i.e. with dislocations that are less mobile.

4 Conclusion

The conducted research has shown that the cooling rate of strip after the hot rolling has a significant effect on the start of the plastic material flow during subsequent cold deformation. At the start of the plastic flow during cold deformation, Lüders bands appear at cooling rate of 6 °C/s. At higher cooling rate 12.4 °C/s, Lüders bands do not appear. It was not found differences in microstructure that could be associated with differences in behaviour of differently cooled samples. The appearance of the Lüders bands can be related to the differences in the density of dislocations and their interaction with the precipitates. These influences will be studied in detail by further research using transmission electron microscopy.

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