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DETERMINING THE AMOUNT OF LÜDERS BAND IN NIOBIUM MICROALLOYED STEEL

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The article presents the results of measuring the amount of deformation during the formation and propagation of Lüders bands through the deformation zone. The amount of deformation was determined by applying the visioplasticity method with digital image correlation, and analyzing the captured images using the MatchID software package. Results show that during the formation of Lüders bands, the deformation of 0,004 mm/mm was achieved. Furthermore, it was determined that during the propagation of Lüders bands through deformation zone, the sample was deformed in the amount of 0,05 mm/mm.

Key words: niobium microalloyed steel, plastic deformation, Lüders band, visioplasticity, digital image correlation

INTRODUCTION

Lüders bands represent the occurrence of inhomogeneous deformation during plastic deformation. The occurrence of Lüders bands has been observed in some aluminium alloys and in some grades of low carbon steel [1-4]. Using static tensile testing it is determined that the formation of Lüders bands starts at the beginning of metals plastic flow, just after the yield point. The research on the phenomena of Lüders bands showed that they occur in alloys which contain the presence of elements C and N, and their compounds, the so-called Cottrell's atmospheres, pin down the movement of dislocations [1,3].

Niobium microalloyed steel is low carbon steel with the addition of micro alloying element niobium from 0,04 to 0,06 wt%. It is a well-known fact that in niobium microalloyed steel there are very small niobium carbo-nitride precipitates, which represent an insurmountable obstacle to dislocation motion.

It has been found that this steel also exhibits the phenomenon of Lüders bands occurrence [4,5].

In the last few years, for the purposes of studying the deformation zone and phenomena of Lüders bands, researchers have been using thermography and visioplasticity methods with digital image correlation (DIC) [6-10]. Dependence of Lüders bands on various parameters such as strain rate, grain size and samples dimensions have been explored to a lesser degree [8,11-12].

Latest research on niobium microalloyed steel [5] confirms the presence of Lüders bands. Their occurrence is explained with the interaction of dislocations and fine niobium precipitates [5]. Yet, the question remains as to the amount of deformation that takes place during the formation and propagation of Lüders band.

The aim of this research is to determine the amount of deformation that occurs during the forming of Lüders band, and measure the amount of Lüders deformation in niobium microalloyed steel by using the visioplasticity method with digital image correlation.

MATERIAL AND EXPERIMENTAL

Research was conducted with static tensile testing at strain rate $\dot{\varepsilon} = 0{,}011\ s^{-1}$. During stretching, the recording of samples deformation was carried out using digital camera (Sony DCR-SR77E) with a CCD sensor. Rectangular samples, dimensions of the gauge section 45 x 20 x 3 mm, were taken in the rolling direction of niobium microalloyed steel strip. The chemical composition of steel is given in Table 1.

Table 1 **Chemical composition / wt %**

C	Mn	Si	P, S	Al	Nb	N
0,12	0,78	0,18	<0,0018	0,02	0,048	0,008

For the method of digital image correlation, random markers of different sizes were applied using black and white paint on a previously prepared surface of samples. Analysis of the recorded markers movement was performed using software package MatchID 2D. From obtained deformation fields, values of local deformations were measured during the formation and propagation of Lüders bands. The study was conducted on a larger number of samples, and representative results are presented in the results and discussion section.

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RESULTS AND DISCUSSION

From the stress - strain diagrams obtained by tensile tests, Figure 1, a certain delay in the rise of stress at the very beginning of plastic flow of microalloyed steel is observed. This was not observed in earlier research on low carbon steel with the same base chemical composition without the addition of micro-alloying element niobium [4]. At specific points during the static tensile test, as shown in Figure 1 (0, A, B, C), the deformation distribution on the surface of samples was recorded and the quantitative values of the amount of deformation were determined. Results are shown in Figure 2.

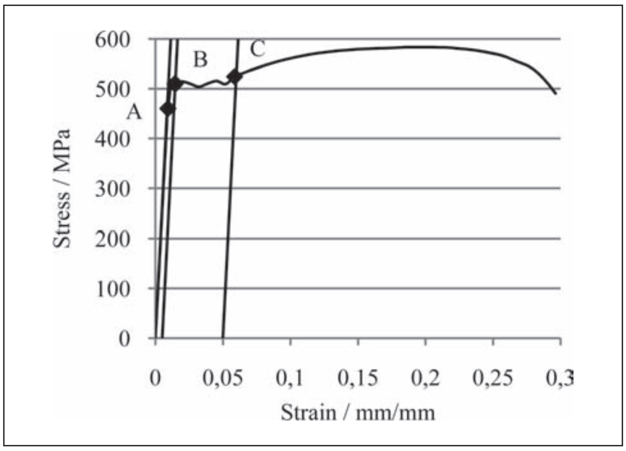


Figure 1 Stress strain diagram obtained by tensile testing

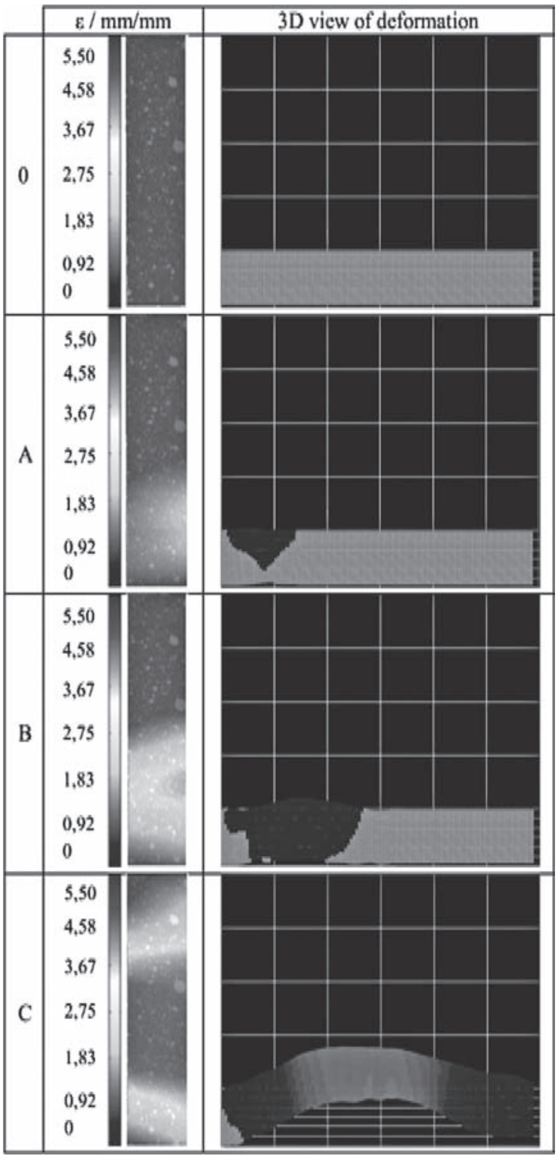


Figure 2 Formation and propagation of Lüders bands, during the static tensile test / see Figure 1.

On the stress – strain diagram (Figure 1), *0 - A* range represents the area of elastic deformation of steel. At the same time, from the obtained deformation maps with DIC analysis, Figure 2, it can be seen that from point *0* all to the point *A* there is not any plastic deformation.

Thermographic tests on microalloyed steel show that in point *A* (Figure 1), there is a sudden increase in temperature, indicating the beginning of plastic flow [4,5]. Simultaneously, DIC analysis indicates that at the point *A* (Figure 2), localized deformation at the one end of the sample occurs.

Point *B* (Figure 1) represents the upper yield point, which is clearly expressed in this steel. DIC analysis, Figure 2, shows how the Lüders band which began to form at point *A*, by reaching point *B* spreads across the width of the sample, thus forming Lüders band along the entire width of the sample. The formed Lüders band is at an angle of 45° relative to the direction of acting force during stretching.

Previous thermographic tests on the same steel show that in the section *B* - *C* (Figure 1) there is a non-homogeneous temperature distribution over the surface of samples [4,5]. At the same time, DIC analysis, Figure 2, shows how the Lüders band starts to move along the length of the test sample from point *B*, reaching the other end of sample in the point *C*. The distribution of deformation during propagation of Lüders bands along the deformation zone of the tested sample is shown in Figure 3.

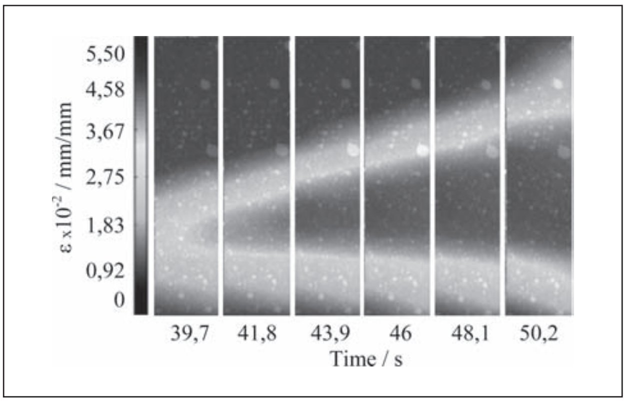


Figure 3 Propagation of Lüders band

The change in strain, which is the Lüders band, Figure 2 and Figure 3, are shown by the change of colour in pictures.

From the recorded deformation maps, Figure 3, it can be seen that during the formation and propagation of Lüders bands, in front of the formed band on the sample only elastic stress state without any plastic deformation takes effect. When the Lüders band front passes, the sample is deformed to a certain amount of strain. After passing, behind the Lüders band there is no significant change in strain and there remains a constant amount of strain which is achieved by the passing of the Lüders front, as seen in Figure 3. This is consistent with previous research via a thermographic camera [5]. Once the line reaches the other end of the sample at point C, Figure 2 and Figure 3, further deformation continues and is located in the central part of the sample.

The results of quantitative measurements of changes in the deformation during the formation and propagation of Lüders bands, obtained with method of the DIC are shown in Figure 4.

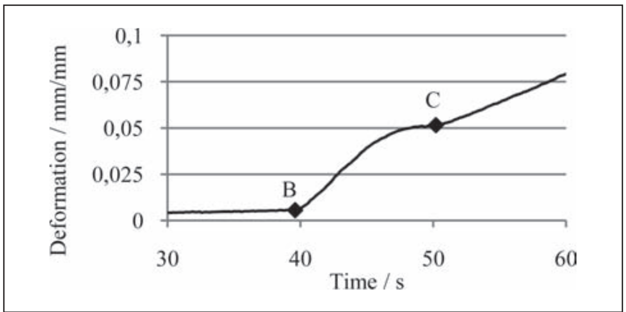


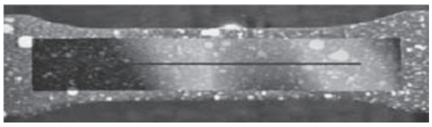
Figure 4 Measured deformation in the area of localized deformation

Quantitative analysis of DIC, Figure 4, shows how up to point *B* there is no significant change in the deformation of the sample. Until then, there is only elastic deformation. At point *A*, just before point *B*, Figure 2 and Figure 3), the formation of Lüders band begins. At niobium microalloyed steel, in the beginning of the plastic deformation, the maximum deformation is localized in one edge of the sample, near the head of the test sample, Figure 2 point *A*. Localized deformation spreads towards the other edge of the sample until it forms a Lüders band. From the results of quantitative analysis with DIC, as shown in Figure 4, it is determined that during the formation of Lüders band across the width of the sample, from point A to point *B* (Figure 1), the achieved strain is in the amount of 0,004 mm / mm.

After point B, Figure 3, there is a sudden change in deformation in a localized part of sample, which can be observed in Figure 4. The deformation further retains a certain constant amount, until reaching point *C*, as seen in Figure 4. The changes in strain along the gauge length of the sample were measured at the specific points of deformation *0*, *A*, *B* and *C*, respectively Figure 5.

The distribution of deformation was measured across the line in the middle of the samples along the entire gauge length of tested samples, as presented in Figure 5 a). It can also be seen that a sudden change of deformation occurs only in a localized part of the sample. Comparing the results with previous results of thermographic

a)



b)

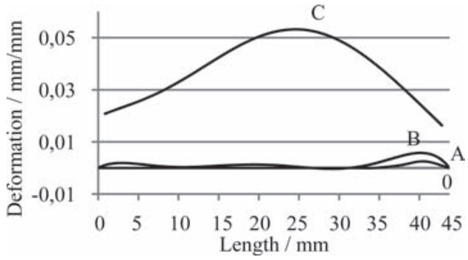


Figure 5 Distribution of deformation along the sample before and after the passage of Lüders fronts
a) Place of measuring deformation
b) Measured deformations along samples

investigations of this steel [4,5,11], it can be seen that a certain period of time is required for the formation of Lüders band.

After the Lüders lines forms, as seen in point B of Figure 2, it gradually moves along the gauge length of the deformed sample. In doing so, the maximum amount of deformation on the sample is measured right on the Lüders band front.

Behind the Lüders band, approximately the same amount of deformation continues, Figure 3 and Figure 4. Quantitative DIC analysis showed that during the Lüders band propagation, the samples are deformed to a certain amount of strain. It has been measured that during the propagation of bands, the samples are deformed up to strain of ε = 0,04 to 0,05 mm / mm. Once the band reaches the other end of the sample, as seen in point C in Figure 2, a continuous increase in the deformation of sample occurs, Figure 4.

CONCLUSION

Measurements conducted in this research have confirmed that during the deformation of niobium microalloyed steel, in the beginning of plastic deformation upon reaching the upper yield point, Lüders bands occur.

The results indicate that Lüders bands are formed in the area between the elastic limit and upper yield point. Using Digital image correlation method, it has been found that the deformation starts at one end of the sample and spreads towards the other end at an angle of 45°. It has been measured that during the formation of Lüders band, the deformation of ε = 0,004 mm/mm is achieved.

Furthermore, it has been measured that during the propagation of Lüders bands along the entire gauge length of the sample, deformation from ε = 0,04 to 0,05 mm/mm is achieved.

During the propagation of Lüders band, behind its front there remains a constant amount of deformation, while on its front a sudden change of deformation takes place, during which there is a transition from elasto-plastic to the plastically deformed state.

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