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Original scientific paper

Line Analysis of Changes in the Deformation Zone During Lüders Band Propagation

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Abstract: In order to determine the Lüders band propagation along the deformation zone length and width as affected by the force action direction, a detailed line analysis is performed by applying thermography and digital image correlation (DIC) during static tensile test at different test positions. The test is stopped at the point when the Lüders band propagation reached its middle to analyse temperature changes and deformations occurring in front of, on and behind the Lüders band front. Line analysis of the test samples confirmed that there are changes in the distribution of temperature and deformations. Across the width of the test sample, there are oscillations and differences in the distribution of temperature changes in the deformation zone. However, the same analysis showed that there are no differences in the change of deformations across the width of the test sample, except in the zone behind the Lüders band front where the Lüders band propagated. The influence of microstructure, i.e. the different dislocation density and the interaction of dislocations with fine precipitates, proved to be the cause of change in temperature and deformations measured at the moment when the Lüders band propagation reached its middle.

Keywords: digital image correlation (DIC); line analysis; Lüders band propagation; niobium microalloyed steel; thermography

1 INTRODUCTION

Different thermomechanical conditions, residual stresses and other parameters, such as strain rate, temperature and deformation degree, have a significant influence on quality of products manufactured by metal forming [1, 2].

During plastic deformation of various steels [3], such as microalloyed steel [4], austenitic stainless steel [5], TRIP steel [6] and bimetals [7], there is a possibility of inhomogeneous deformation occurrence. Inhomogeneous deformations or phenomena that usually occur in metal forming of steel are Lüders bands [8], and Portevin - Le Chatelier effect (PLC) [9]. Lüders bands appear at the beginning of plastic flow, and Portevin - Le Chatelier effect (PLC) occurs continuously from the beginning of plastic flow up to the breaking point of test material. Lüders band, as one of the mentioned phenomena, is usually researched by applying thermography and digital image correlation (DIC) [10]. Under certain conditions, with these methods it can be determined distribution and values of temperature changes (associated with stress changes in deformed metal [10]) and deformation during the plastic flow both of steel and other metal materials [11, 12]. Thermography and DIC results can be presented by line and point analysis, thus analysis of a certain zone of interest that shows appearance and propagation of the Lüders band, but also other phenomena happening during the plastic deformation of steel [13-16]. Lüders band is researched in different ways by developing mathematical models [17], by determining the influence of microstructure [18, 19], strain rate [20], etc. Line analyses obtained by thermography and DIC are used as well to examine Lüders bands. In the study [14], the distribution of temperature changes and deformations from the beginning to the end of the Lüders band propagation were investigated by line analysis, and then the Lüders band was investigated in certain parts during its propagation [15].

However, researches into Lüders band do not offer detailed analysis of the entire cross-section of tested samples at the moment when the Lüders band propagation reaches its middle. For this reason, this research is performed in order to analyse distribution of temperature, i.e. stress, changes and deformation occurring in the middle of the Lüders band propagation by line analysis along the length and width of the test samples.

2 EXPERIMENTAL PROCEDURES

Line analyses of the Lüders bands were performed in different zones of steel microalloyed with 0,048% Nb. Chemical composition of the tested steel is overviewed in Tab. 1.

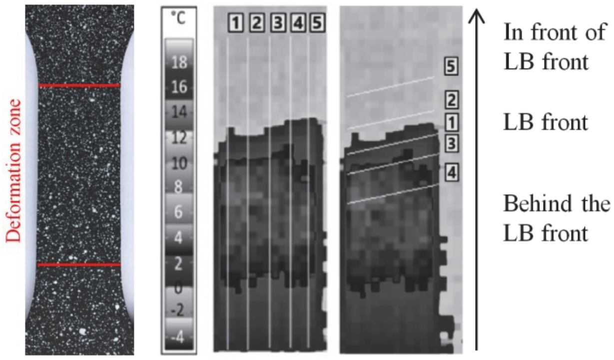
Table 1 Chemical composition / wt %

C	Mn	Si	P	S	Al	Nb	N
0,12	0,78	0,18	0,011	0,018	0,02	0,048	0,008

Test samples were taken from hot-rolled sheet manufactured in industrial conditions. Static tensile test was performed simultaneously with a thermographic and digital camera. The static tensile tests were performed on flat test samples during stretching on a testing machine WPM EU 40 with a measuring range of 0-400 kN. Dimensions of the tested samples were 45 × 20 × 3 mm. The tests were carried out at a stretching rate of 20 mm/min. The JENOPTIK VarioCAM®M82910 thermal camera and the FLIR Blackfly S Color digital camera with 3.2 M pixel were used for recording of test samples during uniaxial stretching. For examination by the thermography, the samples were coated with a black matte coating, ColorMaticLechsys 29141 RAL 9005. During the test, thermography recorded 50 images per second, and DIC recorded 5 images per second, thus ensuring precise determination of temperature and deformation changes during the Lüders band propagation. On previously coated black surface of the test samples white markers, ColormaticLechsys 29141 RAL 9010 was applied, in order to apply digital image correlation. Analysis of the obtained thermography results was performed by IRBIS3 Professional software package, and data obtained by DIC were analysed by MatchID 2D. Such analysis provided qualitative and quantitative results on the distribution of temperature, i.e. stress, changes and on deformations in the test sample measurement zone. Loading of samples was stopped in the middle of the Lüders band propagation.

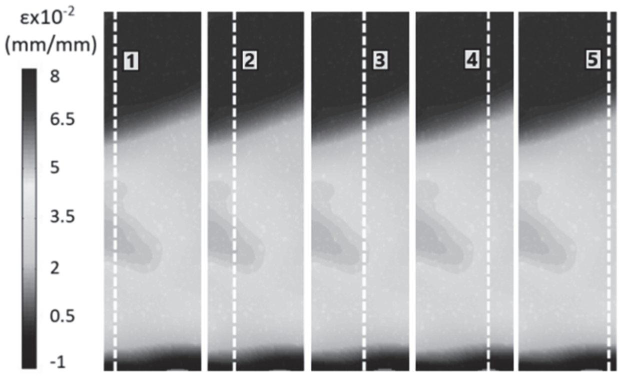
3 RESULTS AND DISCUSSION

At the moment of stopping the Lüders band in the middle of propagation from one end of the test sample to the other end, line analyses are carried out along the length and width of the test samples by thermography and DIC on marked line positions (1-5), as presented in Figs. 1 and 2. Qualitative and quantitative line analysis is performed along the length of the test sample at the moment on the half of the Lüders band propagation. This analysis is performed at five positions of line analysis with lines arranged from left (position 1) to right (positions 2, 3, 4 and 5), as shown in Figs. 1b and 2a.

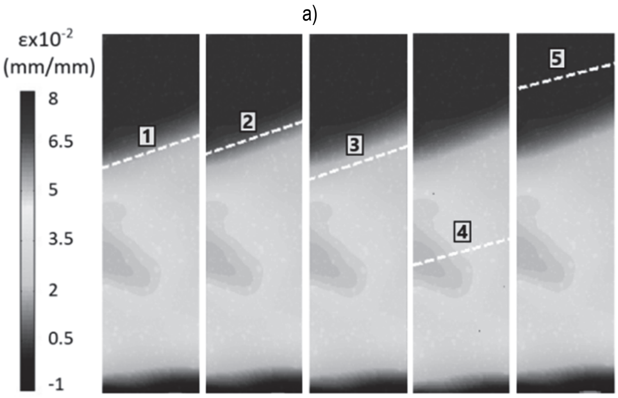


a) b) c)

Figure 1 Line analysis by thermography at positions 1-5 in a) the deformation zone; b) along the length of the test sample and c) along the width of the test sample



a)

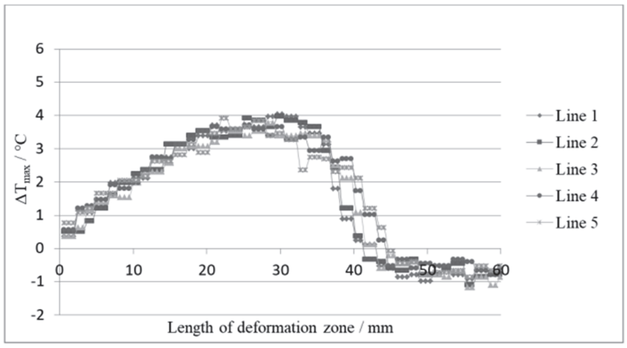


b)

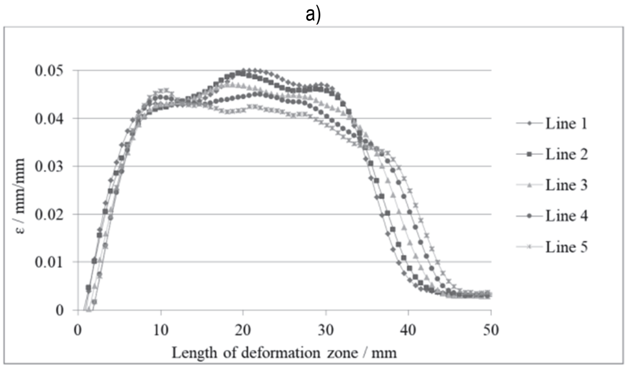
Figure 2 Line analysis by DIC at positions 1-5: a) along the length of the test sample and b) along the width of the test sample

Besides qualitative and quantitative line analysis along the length of the test sample, an analysis is also performed along the width of the test sample, as seen on Figs. 1c and 2b. That analysis is carried out across the width of the test sample in order to obtain the data on distribution and changes of temperature, i.e. stress, and deformation in selected zones: on the Lüders band front (position 1), immediately in front of the Lüders band front (position 2), slightly behind Lüders band front (position 3), behind Lüders band front (position 4), in front of Lüders band front (position 5), as shown in Figs. 1c and 2b.

Qualitative line analysis along the length of the test sample proves that there are visual changes in the values of maximum temperature change and deformation between the zones of the propagated Lüders band and the zones without propagation, i.e. the zones of elastic deformation. Qualitative analysis along the width of the test sample in the zones on and around the Lüders band front (positions 1, 2 and 3), and in front of the Lüders band front (position 5) does not show visually significant changes along the lines that are analysed at a specific position. Therefore, a more detailed quantitative line analysis is performed by thermography and DIC along the length and width of the test sample, as presented on Figs. 3 and 4.



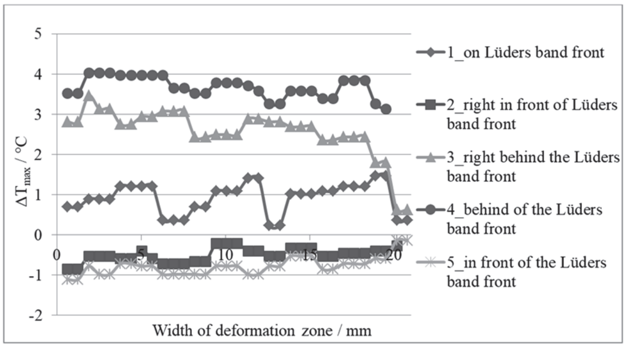
a)



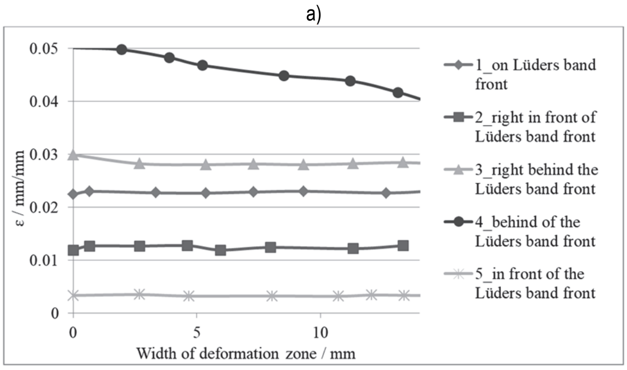
b)

Figure 3 Quantitative line analysis along the length of the test sample at positions 1-5 by: a) thermography and b) DIC

Detailed quantitative line analysis performed at the moment of the middle Lüders band propagation confirmed that there are differences in the zones behind, in front of and on the Lüders band front, as shown by Figs. 3 and 4. Quantitative results of the line analysis along the length of the test sample show that the Lüders band propagated zone (position 4 on the Figs. 1c and 2b) has the greatest change in temperature, i.e. stress, and in deformation when compared to the zone in front of the Lüders band front at all tested positions (1-5), Figs. 3a and 3b. Moreover, there is also a difference determined for the distribution of temperature, i.e. stress, changes and deformations at different positions (1-5) between the Lüders band propagated zone and the zone without propagation, Fig. 3. Detailed line analysis across the width of the test sample in the zone immediately in front (position 2 in Figures 1c and 2b) and immediately behind the Lüders band front (position 3 in Figs. 1c and 2b) proves that there is difference, i.e. oscillation in the values referring to the temperature change across the width of the test sample, Fig. 4a. Deformation values in the same zones remain unchanged across the width of the test sample, as seen in Fig. 4b.



a)



b)

Figure 4 Quantitative line analysis along the width of the test sample at positions 1-5 by: a) thermography and b) DIC

Researches proved that there is a significant interaction between dislocations and fine niobium precipitates in the zones on and close to the Lüders band front during the propagation of the Lüders band [21, 22]. Differences in the distribution of temperature, i.e. stress, across the width of the deformation zone can be associated with changes in the microstructure, as confirmed in [22]. Furthermore, there is no plastic deformation in front of the Lüders band front, while plastic deformation occurs in the zone of the Lüders band. For this reason, the results obtained by line analysis across the width of the deformation zone clearly show that the differences in the distribution of temperature, i.e. stress, changes in front of the Lüders band front (position 5) are lower than in the zone on and behind the Lüders band front (positions 1, 3 and 4) along the entire width of the deformation zone. Analysis performed along the width of the deformation zone shows that the values of temperature changes decrease from the zone behind the Lüders band front to the zone in front of the Lüders band front (from position 4 to position 5). As expected, in the same zones, there was no change in the values and distribution of deformations. Changes and differences (oscillations) in the distribution of deformations across the width of the test sample deformation zone are not confirmed by line analysis. There is no intensive release of dislocations, which would enable their further progress and the increase of deformation, since there is intensive interaction and pinning of dislocations on fine niobium precipitates on and around the Lüders band front, except for the zone behind the Lüders band front (position 4), where the distribution of deformations is not uniform across the width of the deformation zone, but greater values of deformations are determined in the area of localised maximum deformation.

4 CONCLUSION

Qualitative and quantitative line analysis of thermography and DIC at the moment of the middle Lüders band propagation confirms more significant and greater changes in the distribution of temperature, i.e. stress, and deformation in the Lüders band propagated zone than in the zone where the Lüders band did not propagate. Line analysis across the width of the test sample deformation zone proves that there is a difference in the distribution of temperature, i.e. stress, changes which are more significant in the zone behind the Lüders band front. On the other hand, it is determined that the values of deformation in the same zones do not change across the width of the deformation zone, except for the Lüders band propagated zone. Determined values of temperature and deformation distribution across the width of the deformation zone decrease from the zone behind the Lüders band front towards the front of the Lüders band front. Compared to the zones on the Lüders band front and in front of the Lüders band front, the highest values and changes in temperature and deformation are determined by line analysis along the length and width of the test sample in the Lüders band propagated zone, i.e. in the zone of position 4 across the width of the test sample, as shown by Figures 1c and 2b. Changes in the values and distribution of temperature and deformation are caused by the changes in the microstructure during Lüders band propagation, i.e. by the interaction of dislocations with fine niobium precipitates and their release, as well as by different dislocation density in certain zones of the Lüders band.

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