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LÜDERS BANDS AT THE BEGINNING OF THE PLASTIC FLOW OF MATERIALS

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Intensive research into inhomogeneous deformations at the beginning of the plastic flow on different metal materials has been carried out during the last few years. Lüders bands are detected using methods of static tensile testing, thermography and visioplasticity with digital image correlation. This paper is a review of insights into the mechanism of formation and parameters influencing the occurrence and propagation of Lüders bands. Current knowledge indicates that there is not a full explanation of the cause of the Lüders bands formation. There are also certain differences in the way some parameters influence the occurrence of Lüders bands, primarily in different materials. Therefore, modern methods are used to explain the formation of Lüders bands.

Keywords: start of the plastic flow of material, Lüders bands, chemical composition, microstructure, strain rate

INTRODUCTION

The inhomogeneous deformations of some steels and non-ferrous metals were detected a long time ago. By analysis of dislocations during the material flow, Cottrell and Bilby established that inhomogeneous deformation is related to pinning dislocations at certain obstacles [1]. However, inhomogeneous deformation could not completely clarify cold deformation at the beginning of the plastic flow of the material. This phenomenon is again intensively investigated by the development of modern research methods such as thermography and visioplasticity simultaneously with the static tensile testing. Initially thermography was used as a non-destructive (NDT) method. The localisation of deformation and temperature change occur simultaneously and confirm thermography as a suitable testing method of the deformation zone [2]. Visioplasticity with digital image correlation (DIC) used today allows a detail analysis of material flow and amount of deformation in any point of the deformation zone [3].

The connection between inhomogeneous deformation and the occurrence of Lüders bands was noticed [2,4]. Intensive research of formation and propagation of Lüders bands has been carried out on various steels, alloys and in various test conditions. Mainly, the results agree that the occurrence of Lüders bands are related to dislocation motion at the beginning of cold deformation. However, formation and propagation of Lüders bands has not been fully explained so far and discrepancies in the interpretation of influential parameters have been found. This paper gives a review of current knowledge with emphasis on parameters influencing the occurrence and propagation of Lüders bands.

LÜDERS BANDS FORMATION AND PROPAGATION MECHANISMS

Over the last few years, investigation has shown [5] that Lüders bands occur with the appearance of upper and lower yield strength after which the load is visually consistent with only a small strain. Lüders bands usually start at the end of the samples and propagate over the entire gauge length during standard static tensile testing. In niobium microalloyed steel a delay in stress increment at the beginning of the plastic flow of the material is associated with the localisation of deformation at one end of the sample, i.e. Lüders bands, Figure 1. Cai et. al. [6] noticed in 5456 Al-based alloy, the appearance of inhomogeneous deformation, i.e. Lüders bands front inclined at 60 ° with respect to the tensile direction assuming that it was a consequence of the crossover of localized bands with different orientations.

In [7] a comparison of experimental and numerical results in steel led to the conclusion that Lüders band front forms inclined at a certain angle propagating from one end of the sample to the other, thereby separating undeformed (elastic) and deformed (plastic) region of the sample.

Thermography testing of deformation zone evolution in niobium microalloyed steel has shown the existence of Lüders strains at the beginning of plastic flow of these steels [8]. In [9] it is stated that in niobium microalloyed steels Lüders bands propagate along the sample in such a manner that, with dislocation pinning at arrays of niobium precipitates, work hardening and stress increment occur in the deformed region. Temperature and

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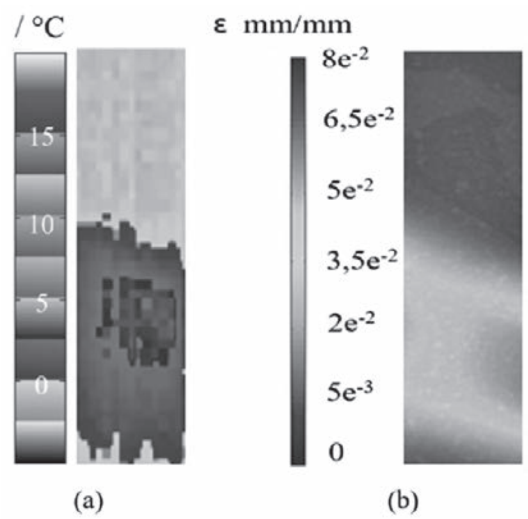

Figure 1 Lüders band detection using two methods: a) thermography and b) digital image correlation (DIC)

deformation distribution related to pre-yield microstrain were investigated in IS 2062 grade-E250 B steel. Inhomogeneous pre-yield strains are attributed to microstrains in this field which can be associated with places of Lüders bands formation [10].

Appearance of several Lüders bands

Srinivasan et. al. [5] established the appearance of two Lüders bands in mild steel IS 2062 grade B and concluded that shear strain has a major role in Lüders band deformation. In their further research, occurrence of the second Lüders band in the lower half of the sample after the propagation of the first band in the upper half of the sample was observed. It is considered that formation of the second Lüders band, as aforementioned, occurs due to the delayed yielding of certain grains within the band front. Sun et. al. [4] observed that the number of Lüders bands in the annealed low carbon steel during the testing is not always identical and explained it as a great sensitivity of Lüders bands formation at different stress concentrations in the samples.

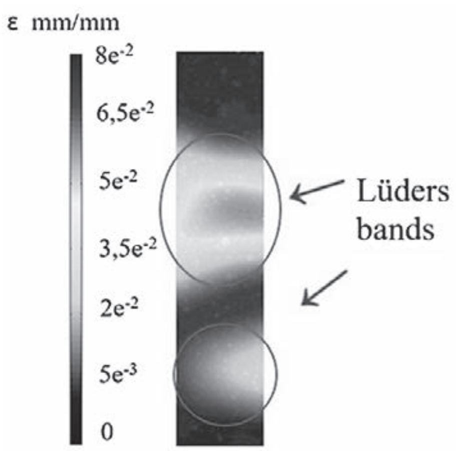

Figure 2 The appearance of two Lüders bands in niobium microalloyed steel

The appearance of several Lüders bands in niobium microalloyed steel has also been detected, Figure 2.

The review showed that several Lüders bands occur in various types of steels during plastic deformation but there is no clear and generally accepted explanation of the cause of their appearance.

INFLUENTIAL PARAMETERS OF FORMATION AND PROPAGATION OF LÜDERS BAND

A number of studies on various steels, as well as copper and aluminium alloys have been undertaken. Testing differences were chemical composition, initial structure as well as difference testing conditions, e.g. at different strain rates, and shape and dimensions of the sample etc. These differences did not provide an explanation of certain factors influencing the formation and propagation of Lüders bands.

Influence of chemical composition on the appearance of Lüders bands

Recently, research has been carried out on various materials, mainly low carbon steels [11], aluminium alloys [6] and transformation induced plasticity (TRIP) steels. Studies on low carbon steel and low carbon steel with the same base chemical composition with the addition of micro-alloying element niobium [8], have shown the appearance of Lüders bands only in niobium microalloyed steel and it is related to niobium precipitates. The appearance of Lüders bands have been observed in C-Mn steel [12] where Lüders strain decreases with the increase of the carbon content while [13] small quantities of pearlite reduce the Lüders strain. Lüders bands have also been identified in low carbon steel [11] establishing the fact that Lüders elongation decreases with the increase of carbon content. Investigations of various materials have shown the appearance of Lüders bands only in some materials and further research is required to clarify entirely the influence of the chemical composition.

Influence of microstructure and grain size on the magnitude of Lüders strain

Johnson et. al. [13] examined the influence of microstructure on the magnitude of Lüders strain in low carbon steel. Studies were carried out on low carbon steels with different microstructures. They show that in the steels with the same chemical composition but different microstructure, Lüders strain is the lowest when the microstructure is ferrite-pearlite or upper bainite whereas materials with a tempered martensite structure have higher Lüders strains. These are associated with a different morphology of carbides in different microstructure [13]. Other authors affirm that Lüders strain decreases with the increase of grain size. Tsuchida et. al. [11] established a higher Lüders elongation of annealed hot rolled ferrite-cementite and ferrite-pearlite low carbon steel with a decrease of grain size.

The influence of strain rate on the appearance of Lüders bands

Lately the influence of strain rate on the occurrence and propagation of Lüders bands is studied. Research [13] carried out on low carbon steels has shown a slight increase of Lüders strain with the increase of strain rate. In the low carbon steel with ferrite-pearlite structure and higher carbon content, Lüders strain increment with strain rate increase is less evident. Sun et. al. [4] established by static tensile testing with physical equations the increase of Lüders bands velocity and strain increase with strain rate in annealed low carbon steel. Nevertheless, Cai et. al. [6] observed on annealed 5456 Al-based alloys that there is no power-law dependence between strain rate and Lüders strain and noticed that Lüders strain mostly increases with the increase of the strain rate, but with some unexplained deviations, which contradicts previous studies [4,13].

The comparison of data in the quoted references has shown a slight effect of strain rate on Lüders strain in steel samples unlike samples of aluminium alloys. Also, it seems that the influence of strain rate on the amount of Lüders strain has been partially associated with the microstructure of the material, and the carbon content, but there is no clear explanation how strain rate exactly affects the amount of Lüders strain.

The influence of sample thickness on Lüders bands

The influence of sample thickness on Lüders bands has been studied as well. Cai et. al. [6] examined for the first time the effect of sample thickness on the Lüders bands in 5456 Al-based alloy. It was proven that Lüders strain increases and Lüders band velocity decreases with the decrease of sample thickness.

CONCLUSION

In recent years, research has shown that the appearance of the Lüders bands is associated with the localisation of the deformation. Lüders bands propagation mechanism has been well explained but there is not a full and generally accepted explanation of the cause of the Lüders bands formation. The occurrence of these bands is not thoroughly examined and the influence of chemical composition or micro-alloying elements has not been clearly explained. The appearance of several Lüders bands has been observed, however, a clear cause of the occurrence of several Lüders bands in various materials is not fully explained. The influential parameters of the occurrence and amount of Lüders strain in some cases vary from material to material. Certain influential parameters, such as impact of sample thickness and strain rate on the Lüders bands appearance in materials with different chemical composition are not investigated sufficiently. It has been established that Lüders strain decreases with the increase of grain size, however, the physical mechanism of this effect and of other effects is not fully understood. It is considered that the microstructure has a significant impact on the formation and propagation of the Lüders bands. Thus, there is a justification for further extended microstructural studies, such as determination of the grain orientation during deformation.

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Note: The responsible translator for the English language is Ivančica Puškarić, M.A., Sisak, Croatia