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Study On The Deformation Band Characteristics In Mild Steel Using Digital Image Correlation

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***Abstract*— This study investigates the strain localizations associated with Lüders deformation in mild steel using digital image correlation (DIC), a non contact, nondestructive, full field measurement technique for strain mapping. The focus is on the two substantial areas of interest such as shear deformation accompanying strain localization during Lüders instability and the complex morphology of Lüders deformation bands. The results provide insights into nature of shear deformation associated with the Lüders band front propagation (band growth) and some important morphological features of complex Lüders band.**

***Keywords*— mild steel; digital image correlation; shear strain; complex Lüders band; yield point phenomena**

I. Introduction

Strain ageing in materials such as low carbon steels, mild steels and Al-Mg alloys leads to an unstable elastic-plastic transition and plastic flow commonly called as plastic instabilities, which deteriorates the formability and ductility of such steels. Lüders deformation is a kind of plastic instability that occurs due to static strain ageing involving interaction of interstitial solute atoms with the dislocations during material storage resulting in pinning of dislocations by solute atmospheres. Lüders phenomenon is characterized by discontinuous yield points in the load-elongation curve, namely upper and lower yield points [1]. The upper yield point corresponds to the unpinning of pinned dislocations or generation of fresh dislocations in a local region leading to formation of cluster of yielded grains called Lüders band. The lower yield point and the following load plateau correspond to yielding of region ahead of the band front leading to increase in number of mobile dislocations. The collective and self-organized movement of these mobile dislocations manifests as band front propagation (band growth) on the surface of the material. Lüders bands induce surface roughness thereby affecting the surface quality of sheet metal products during metal forming operations. Lüders deformation is then followed by uniform strain hardening in the load-elongation curve. Although Lüders instability has been studied over many years, kinematics of strain localization accompanying Lüders deformation and the corresponding macroscopic manifestations are yet to be fully understood. The need for better understanding of the Lüders phenomenon through versatile characterization tools is in demand even today. Till date, many techniques such as optical and electron microscopy [2-3], photography [4-6], extensometers [7], strain gauges [8-9], acoustic emission [10-11], magnetic Barkhausen noise emission [12-13], speckle interferometry [14], infrared thermal imaging [15-18] and digital image correlation [19-22] etc., have been used to study the nucleation and growth behavior of Lüders bands and the macroscopic band characteristics such band front velocity, orientation and band width. However, very limited works has been reported on the complex nature of Lüders band morphology [5-6]. Lomer [5] has reported that fine grained, slender specimens produce sharp planar bands and thick specimens produce complex bands. Ananthan et al. [6] have observed that with increase in test speed complex bands are observed even in then specimens. Authors have also reported that shear contribution to total Lüders strain is higher in fine grained specimen. But, the nature of shear strain evolution during nucleation and growth of Lüders bands has not been completely understood.

Among the techniques employed in the past, infrared thermal imaging and digital image correlation have been used intensively to study plastic instabilities as it is possible to study the spatiotemporal evolutions of strain localization in materials using these techniques [23-24]. Since thermal field is affected by thermal diffusion, identification of strain localization zone becomes difficult (especially in materials with high thermal diffusivity) which is not an issue with DIC thereby making it more suitable technique for mapping strain localizations precisely. In this work, authors focus on the application of DIC to study the nature of complex deformation band and shear strain fields associated with Lüders instability.

II. Experimental

The experimental setup encompasses a 100 kN displacement controlled, electromechanical, screw driven tensile testing machine and CMOS camera associated with DIC system as shown in Fig. 1. The CMOS camera with 1380 x 1035 pixels resolution and

6.7 µm pixel size led to a field of view of 214 x 161 mm and 155 µm spatial resolution for the focal distances set in this study. The CMOS camera was focused on the flat surface of the specimen which is coated with random dot pattern to achieve varying grey levels and perform image correlation. This pattern is generated by first coating the specimen surface with matt white paint followed by manual marking of fine random black dots using a marker pen. Uniform illumination on the surface of the specimen is achieved using a LED light source.

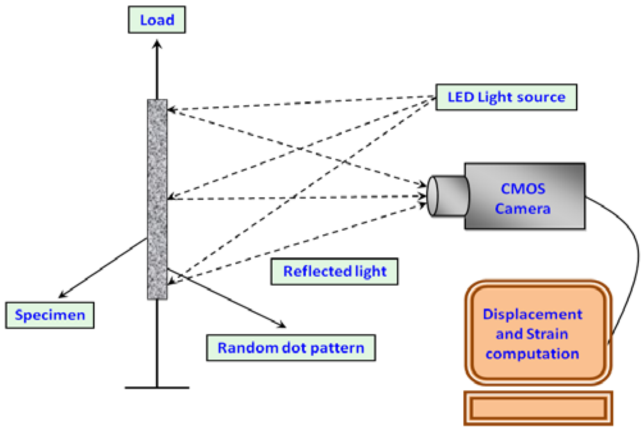

Fig. 1 Schematic of experimental setup

The material used in this study is IS 2062 grade B mild steel which is a general purpose industrial structural steel commonly employed as pipes, plates, hydraulic press structures, durable storage containers, pressurized storage tanks, hydraulic clamps, spindles etc. The chemical composition of this steel is 0.22 wt % C, 1.5 wt % Mn, 0.045 wt % S, 0.045 wt % P and 0.4 wt % Si with carbon atoms playing the role of solute atmospheres. The experimental procedure involves recording the digital images of the specimen with dimension 100 mm x 25 mm at 10 Hz frame rate during quasi static, monotonic, uniaxial tensile testing. Though field of view is covered in the CMOS camera is sufficient enough to study even the fillet region of the specimen, the strain analysis carried out throughout this study is restricted only to the gauge length (covering 100 mm). Strain fields were obtained by performing image correlation using commercially available Vic-2D digital image correlation processing software from.

III. RESULTS AND DISCUSSION

A. *Shear strain evolutions accompanying Lüders bands*

Fig. 2 depicts load-time curve for 4 mm thick specimen deformed at 3 mm/min test speed from which the load plateau involving strain localizations in the form of Lüders bands is identified to be in the range of 69 s to 110 s. The longitudinal (*eyy*) and shear (*exy*) strain fields of the complete gauge length of the specimen (obtained using DIC) exhibiting Lüders deformation in the load plateau is shown in Fig. 3.

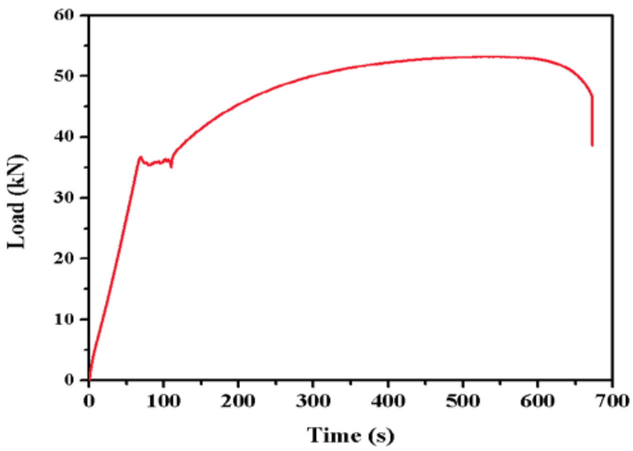

Fig. 2 Load-time curve for 4 mm thick specimen deformed at 3mm/min crosshead velocity

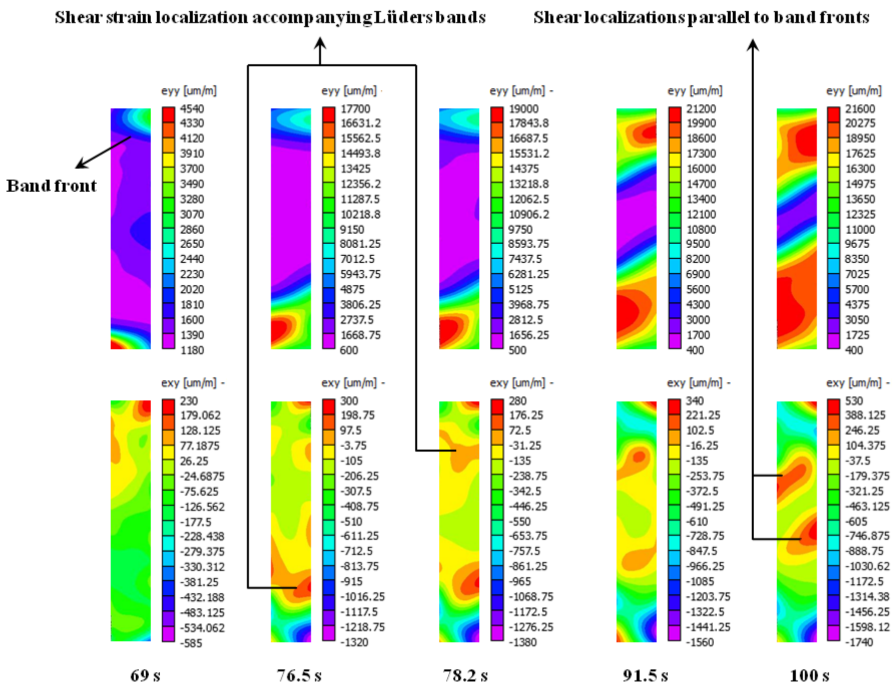

Fig.3 Longitudinal and shear strain localization during nucleation and growth of Lüders bands

At 69th s corresponding to the beginning of load plateau, two bands from either ends of the gauge length nucleate with shear strain evolutions localized within the band. As time proceeds, during the propagation of the band fronts, it is observed that shear strain evolutions are localized at the band front whereas within the band they are negligible. This observation clearly indicates that shear component of the acting stress plays primary role in the growth of the Lüders band (or propagation of the band front) than the flow component. In other words, it is under the influence of the shear component of the total stress the pinned dislocations ahead of the band front are unpinned (or fresh dislocations are generated) leading to movement of the band front. These observations are also in line with the theoretical estimations of shear and flow components of stress carried out earlier [6]. The orientation of the shear front is also observed to be at the same angle as same as that of the band fronts (~ 45 º, the plane of maximum resolved shear stress). This observation corroborates the report of slip lines close to the Lüders band front that are parallel to the band front through electron microscopy [3].

B. Complex Lüders bands

The evolution of complex morphology of Lüders bands is shown in Fig. 4 for a 1.6 mm thick tensile specimen deformed at a lower test speed of 1 mm/min through the DIC strain maps. The load variation involving Lüders deformation is identified to be in the range of 30 s to 51 s from the load-elongation curve shown in Fig. 5. To initiate the formation of complex Lüders bands, the specimen was initially subjected to compressive loading leading to slight bending of the specimen, before being subjected to tensile loading, thereby inducing stress concentrations along the gauge length of the specimen. At 30th s corresponding to the beginning of the load plateau, the strain evolutions are localized in the center of the gauge length unveiling the region of induced stress concentration. Revealing stress concentration zone as the potential nucleation site of complex bands, first complex band evolves close to the stress concentrated zone at 33 s at an angle as seen in Fig. 4. Following this, another complex band evolves from the other side of the stress concentrated zone in a different angle at 40 s with further deformations taking place only within these bands as seen at 45 s. Later, third complex localization takes place at 50 s between the stress concentrated zone and the second complex band. It is to be highlighted that orientations of complex band fronts are random with preferential nucleations at the stress concentrated zone or edge of another band. This observation also proves the formation of complex Lüders bands in slender specimens at lower cross head speeds but under the influence of stress concentrations. It is to be highlighted that load variations involving formation and propagation of complex bands does not resemble a plateau unlike the case of planar band fronts discussed earlier in Fig. 2. The load variations have been found to increase continuously with nucleation and propagation of successive complex Lüders bands as seen in the inset in Fig. 5.

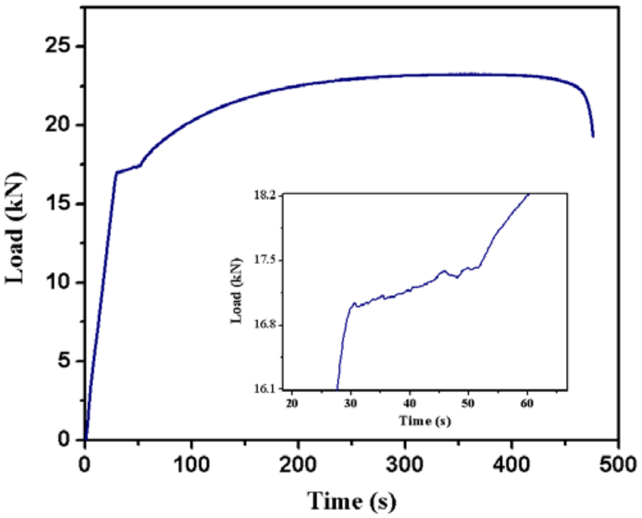

Fig.5 Load elongation curve for 1.6 mm thick specimen with induced stress concentration deformed at 1 mm/min crosshead velocity

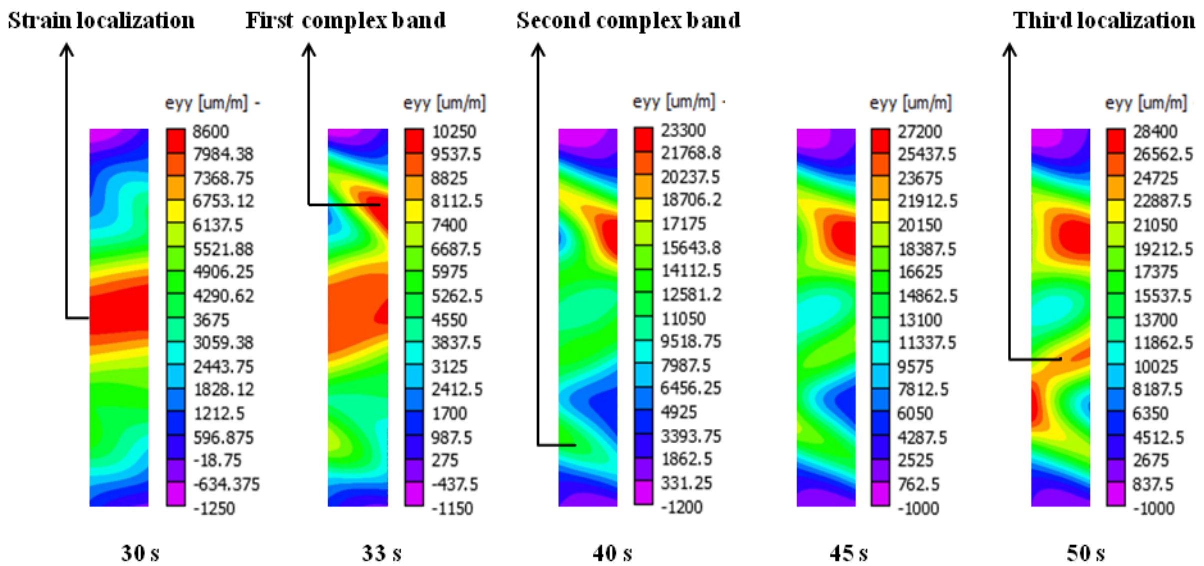

Fig. 4 Strain fields revealing morphology of complex Lüders bands

IV. Conclusion

To summarize, shear strain evolutions and morphology of complex Lüders band are studied using digital image correlation. Shear deformation is localized at the band front during growth of the band with the same angle of orientation as that of the Lüders band front revealing its primary role in band deformation. The study also demonstrated the formation of complex Lüders bands in thin specimens at lower test speed in the region of stress concentrations with increasing macroscopic flow stress. The orientation of the complex band fronts is found to be random unlike the planar band fronts.

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