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[1.] Milija KRAIŠNIK, [2.] Dragiša VILOTIĆ, [3.] Leposava ŠIĐANIN, [4.] Žarko PETROVIĆ,
[5.] Milan ŠLJIVIĆ, [6.] Milentije STEFANOVIĆ

MORPHOLOGY OF STEEL C45E MICROSTRUCTURE DURING UPSETTING

[1,4.]University of East Sarajevo, Faculty of Mechanical Engineering, East Sarajevo, BOSNIA & HERZEGOVINA
[2,3.]University of Novi Sad, Faculty of Technical Sciences, Novi Sad, SERBIA
[5.]University of Banja Luka, Faculty of Mechanical Engineering, Banja Luka, BOSNIA & HERZEGOVINA
[6.]University of Kragujevac,Faculty of Engineering, Kragujevac, SERBIA

Abstract: Entirely understanding of all factors and mechanisms which influence nucleation and accumulation of ultimate level of material failure is necessary for adequate choice of material and rational projecting of metal forming technological procedure. The first step in research refers to the morphology characterization of material micro constituents during processing. This paper contains qualitative-quantitative analysis of morphology changes of ferrite and colonies of pearlite in the steel C45E microstructure during upsetting of cylindrical specimen with flat dies. Relative microforming level of ferrite grains was determined based on direct measurements, while indirect way has been suggested for determination of pearlite colonies forming ability. The approach is based on monitoring of area fraction changes of pearlite colonies in relation to area fraction of ferrite basis during upsetting process. The results of SEM testing have shown that ferrite grains and pearlite colonies are formed unequally.
Keywords: morphologychanges, microstructure, ferrite, pearlite, upsetting, steel

1. INTRODUCTION

Plastic metal forming is highly productive technology which integrates a number of methods for production of components with wide application spectrum. Nonetheless, plastic metal forming can also be defined as a process of controlled change in dimension and shape of the specimen which takes place simultaneously with continuous change in stress-strain state and forming conditions. Under such circumstances it is inevitable that morphological changes and physical damage of material micro constituents occur. It is a progressive and almost all the time unwanted process followed by continuous action of various mechanisms of nucleation, growth and coalescence of micro voids which makes a cumulative impact to reduction of material formability [1].

Phenomenon of material damage in the plastic forming processes has been a subject of many researches. In the process, different theoretical and experimental approaches were used and their common characteristic was well accepted opinion that microvoids are generated in the initial forming stage, much earlier than the occurrence of macroscopic material damage[2-9].

In the studies conducted by Avramović-Cingaraet al.[10-11] three important facts about the impact of morphology and volumetric fraction of micro constituents to mechanical properties and steel formability were stated: increase of volumetric fraction of secondary phases has strong impact to reduction of tension properties, under constant volumetric fraction, uniform distribution of microstructure enables better combination of mechanical properties and plasticity, morphology and orientation of secondary particles, especially hard carbides, has very important role in intensity of accumulation of steel microstructure critical damage level.

Ishiguro et al.[12] have also stated that volumetric fractionof some micro constituents has dominant impact to intensity of micro-fractures' nucleation intensity and microgrowth.

According to the analysis of available literary resources it is evident that the majority of research has been focused to the characterization of morphological changes and quantification of microstructure damage in the forming processes with dominant impact of tension components of the stress. However, there is a smaller number of published papers (i.e. Baloš and Šiđanin [13]) in which the above mentioned the research is aimed to upsetting processes. We can generally state that the results obtained are not sufficient for full understanding of behavior of micro constituents under the impact of upsetting stress. Previously mentioned assessment has been the driving force to turn realization of research in this paper toward cylinder upsetting model.

Primary aim of this research is an attempt of qualitative and quantitative characterization of morphological changes to ferrite-pearlite microstructure in the process of steel cylindrical specimen upsetting. Special efforts were made in defining the approach for determination of pearlite colonies' morphological changes due to the fact that different orientation of cementite lamellae can has significant impact to research results.

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2. EXPERIMENTAL RESEARCH

For the purpose of experimental research we used cylindrical specimens with starting dimensions Ø25x20 mm. Specimens are made of C45E steel in normalized state (SRPS EN 10027-1). Material is in the group of medium carbon steel and it has the purpose of thermal treatment of improvement(SRPS EN 10083-2). However, higher values of mechanical characteristics of steel can also be obtained by cold bulk forming processes, which provides possibilities for wide use in machine industry.

Chemical composition of C45E steel was tested in metallurgical and chemical laboratory of Kikinda Foundry on optical emission spectrometer ARL-2460 (Table 1.).

Table 1. Steel C45E chemical composition

Chemical element	C	Si	Mn	S	Cr	P	Cu	Ni	Mo	V	Al	Sn
Mass fraction[%]	0,46	0,23	0,668	0,026	0,121	0,021	0,17	0,054	0,011	0,006	0,018	0,005

Specimen upsetting was performed on triple impact press „Sack & Kieselbach" with nominal force6,3 MN. Press is installed in the forming laboratory at the Department for Production Engineering at Faculty of Technical Sciences in Novi Sad. Specimens were upset by flat plates with different forming height levels (i.e. I-C40 ⟶ $\varphi_h \approx 0,4$). Final series of upsetting were performed to the level which defines limit formability. Figure 1 represents of forming force change depending on tool stroke F=f(s), which represents schematic plan of specimen upsetting for the purpose of testing morphological changes in steel C45E microstructure. Specimens after upsetting are shown in Figure 2.

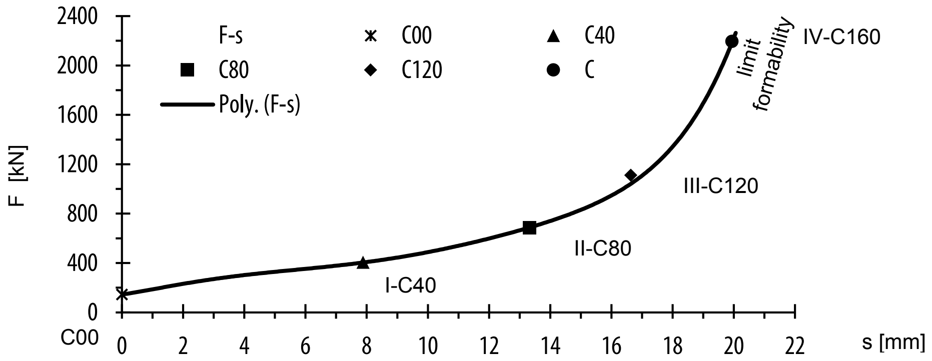

Figure 1. Scheme of upsetting of cylindrical specimens by flat plates for the purpose of SEM research

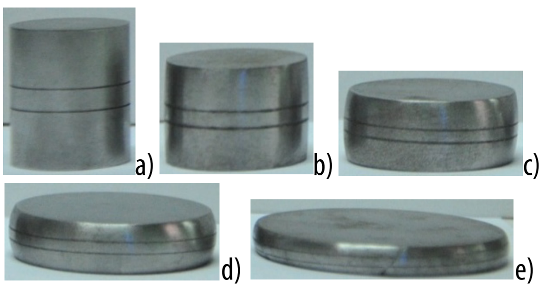

Figure 2. Cylindrical specimens: a) C00 - $\varphi_{h0}=0$, b) C40- $\varphi_{h1}=0,38$, c) C80 - $\varphi_{h2}=0,75$, d) C120 - $\varphi_{h3}=1,10$i e) C160 - $\varphi_{h4}=1,59$ (limit formability)

Before of microstructure testing on Struers equipment there was conventional preparation of metallographic specimens which consists of cutting, multi-level sanding, polishing and etching.Etching was performed in 2% solution of nital. For the characterization of morphological changes in steel C45E microstructure we applied light microscope (LM) and scanning electronic microscope (SEM). Tests were performed onunformed specimen and on specimenswhich were upset on different forming height levels. In the process we used computer-supported Leitz "Ortoplan" light microscope and scanning electronic microscope JOEL JSM-6460LVwith 20 kV voltage and objective lens working distance WD 11 mm. For the purpose of elimination of electroncompacting and obtaining clear image with expressed details, etched specimens were steamed with gold for 90 seconds in the vacuum steamer BAL-TEC SCD 005.

Metallographic research was realized at University Center for Electronic Microscopy Novi sad and Material Research Lab, Department for ProductionEngineering at Faculty of Technical Sciences in Novi Sad.

Metallographic research results were computer processed using specialized software JMicroVision v1.27. Software was used for the purpose of determining the level of relative micro-deformation of ferrite grains for different forming levels of the specimen (1D measurements) and surface fraction of ferrite or pearlite colonies (2D measurements).

3. RESULTS AND DISCUSSION

3.1. Unformed microstructure

Testing with light microscope indicated very small amount of non-metallic inclusions to the steel. Testing results of unformed microstructure in the cross section of the specimen obtainedby LM are presented in Figure 3. Steel C45E microstructure consists of ferrite grains and lamellar pearlite colonies. Size of ferrite grains according to ASTM standard is 8 which corresponds medium size of 22 µm, and pearlite colony is 6 – medium size 44 µm. Surface or volumetric fraction of pearlite colonies is around 60%.

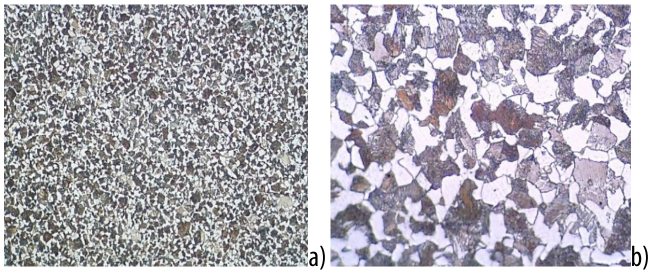

Figure 3. Unformed steel C45E microstructure (SM); a – 10 μm; b – 20 μm

3.2. Formed microstructure

Morphology of longitudinal section microstructure for different forming levels is presented in Figure 4. Results indicate during the upsetting process fiber microstructure gradually forms. Elongation in radial direction is visible even at lower forming levels of the specimen. Morphological changes to microstructure are the most prominent in the final forming phase when level of forming reaches forming limit values. It is visible from the figure 4d that crystal grains are highly formed in radial direction. Flow directions and level of relative micro-deformation are particularly prominent in ferrite grains. Besides the above mentioned, there are micro-crack present inside the formed ferrite grains, especially in the zone of shear instability (mark B).

3.3. Quantification of microstructure changes

Metallographic research results indicate that during upsetting of cylindrical specimens ferrite grains and pearlite colonies form unevenly. In order to determine the level of relative micro-deformation of ferrite we performed quantitative measurements of morphological changes to ferrite grains for all the forming levels consecutively and in accordance with forming scheme presented in Figure 1.

Based on average values of changes to size of ferrite grains in the direction of upsetting axis, we defined the criteria of relative micro-deformation, as follows:

$$\varphi_F = \ln\frac{h_{iF}}{h_{(i-1)F}} \cdot 100 \ \ [\%] \qquad (1)$$

where: h_{iF} and h_{i-1F} are average values of ferrite grains in the direction of upsetting axis for i or i-1 forming level specimen height.

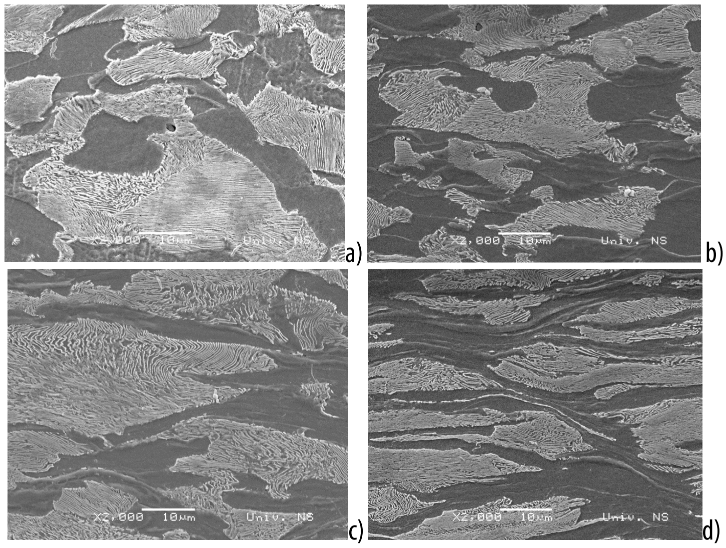

Figure 4. Microstructure of specimens for different forming levels (SEM x 2000)
a) Specimen C40 - $\varphi_{h1} = 0{,}38$; b) Specimen C80 - $\varphi_{h2} = 0{,}75$;
c) Specimen C120 - $\varphi_{h3} = 1{,}10$; d) Specimen C159 - $\varphi_{h4} = 1{,}59$

Equation (1) has enabled determination of increment to the level of relative micro-deformation of ferrite grains ($\Delta\varphi_F$) for particular the forming levels of the specimen consecutively. Incrementof specimen forming level height ($\Delta\varphi_h$) are determined during upsetting according to the plan presented in Figure 1. Results comparison is presented in Figure5.

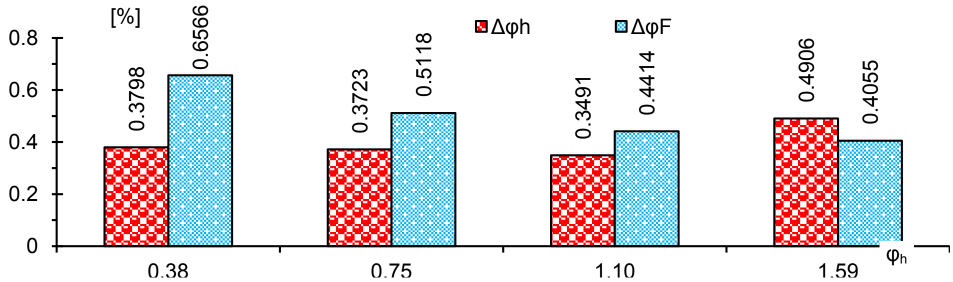

Figure 5. Comparison of specimen forming level height increment and level of micro-deformation to ferrite grains

Direct determination of level of relative micro-deformation of pearlite colonies is very difficult due to powerful impact of orientation of cementite lamellas to forming possibility. For that reason we decided to apply indirect approach based on determining the changes of surface fraciton of pearlite colonies in relation to surface part of ferrite basis during upsetting.

Representative results indicate average values of surface fraciton of pearlite colonies for all the specimen upsetting phases consecutively. Surface fraction of ferrite is determined under the assumption that there are no non-metallic inclusions in the steel. Graphic interpretation of the results is presented in Figure 6.Changes in surface fractionof ferrite and pearlite colonies in steel C45E microstructure depending on forming level of cylindrical specimen are described analytically by second degree polynomial:

- for ferrite: $F=2{,}61\varphi_h^2-12{,}96\varphi_h+42{,}87$,
- for pearlite collonies: $P=-2{,}61\varphi_h^2+12{,}96\varphi_h+57{,}13$

where high level of value for correlation coefficient was achieved $R^2 = 99{,}88\ \%$.

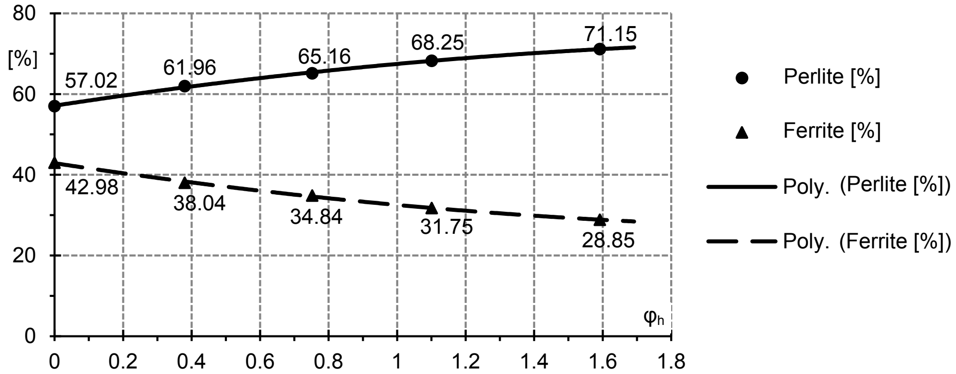

Figure 6. Change in surface fractionof ferrite and pearlite colonies in the steel microstructure of C45E steel during upsetting

4. RESULTS DISCUSSION

Morphological changes quantification results indicate that forming of ferrite grains during upsetting process to cylindrical specimen under relatively uniform increment of specimen forming height level, it is not uniform (Figure 5).

The highest level of relative micro-deformation to ferrite (φ_{F1}=0,6566) was achieved in the initial phase, which is by 72,88% greater value compared to specimen forming level (φ_{h1}=0,3798). With the increase of external pressure load, the ability of plastic forming of ferrite continuously reduces and in the final upsetting phase the increment to the level of relative micro-deformation of ferrite achieves the lowest value ($\Delta\varphi_{F4}$=0,4055) or by 17,35% lower than increment of specimen forming level ($\Delta\varphi_{h4}$=0,4906). Such result was anticipated having in mind the properties of ferrite.

As it has already been pointed out, direct determination of level of relative micro-deformation to pearlite colonies is very difficult. Pearlite colonies at the identical specimen forming level behave differently depending on the orientation of cementite lamellas. If two colonies of identical initial size are analyzed, achieved level of relative micro-deformation in the direction of upsetting axis will be significantly greater for the colony with mostly parallel orientation in relation to normal orientation of cementite lamellas. Therefore, verification for different values of relative levels of micro-deformations achieved on ferrite grains and pearlite colonies was performed indirectly.

Presented results indicate increase of surfacefraction of pearlite colonies that follows from the specimen forming level. However, the increment to surfacefractionof pearlite colonies (ΔP) for individual upsetting phases ($\Delta\varphi_h$) are different and they have a tendency to decrease. Explanation of such phenomenon can be based on the fact, that in the beginning of the upsetting process, when forming hardening is reduced, intensive forming of soft ferrite basis occurs. Under such circumstances forming of pearlite colonies is not uniform and it occurs mainly in the colonies where parallel orientation of cementite lamellas is dominant (in relation to upsetting axis). In that process, pearlite colonies with normal orientation of cementite lamellas have very low level of relative micro-deformation. With the increase in forming level the stress on the border lines of pearlite colonies changes, influencing the increase to relative micro-plastic forming of ferrite in the pearlite. It still induces concentration of stress on the border surfaces of cementite lamellas. When the concentration of stress reaches limit value, cementite lamellas crack and level of relative micro-deformation to pearlite colonies increases.

In the end, it is important to point out that exposed approach to the analysis of results of morphological changes to microconstituents of carbon steel with pearlite-ferrite microstructure was not found in the available literature. However, relatively similar approach was used by Baloš and Šiđanin[13] in defining the level of micro-deformation of microconstituents of nodular cast.

5. CONCLUSIONS

According to the experimental research we can conclude the following:

- Steel C45E microstructure is normalized in the state of delivery and it consists of ferrite grains and lamellar pearlite colonies with different orientation of cementite lamellas in relation to upsetting axis. Ferrite grains are relatively uniformlydistributed on the boundaries of peralite colonies. A very small amount of non-metalicinclusions was noted.
- In the process of upsetting the cylindrical specimen fiber microstructure gradually forms in radial direction. Results of SEM tests have shown that ferrite grains and pearlite colonies are non-uniformly formed.
- Forming of ferrite grains under relatively uniform level of specimen forming is also non-uniform. The highest level of relative micro-deformation to ferrite (φ_{F1}) was achieved initially in the upsetting process and it is by 72,88% greater than specimen forming level (φ_{h1}). During further forming the level of relative micro-deformation of ferriteis reduced and in the final upsetting phase it is by 17,35% lesser than limit specimen forming level.

- Determining the morphological changes to pearlite colonies by direct determination of relative micro-deformation level is difficult due to different orientation of cementite lamellas in relation to upsetting axis. Therefore, in this paper is suggested indirect approach based on following the changes of surface fraction of pearlite colonies in relation to surface fraction of ferrite basis.
- Quantitative analysis results indicate increase of pearlite colonies' presence on the tested surface following the forming level. In that process there is a negative trend of increment which is a result of reduced forming ability of pearlite colonies as the forming level increases.

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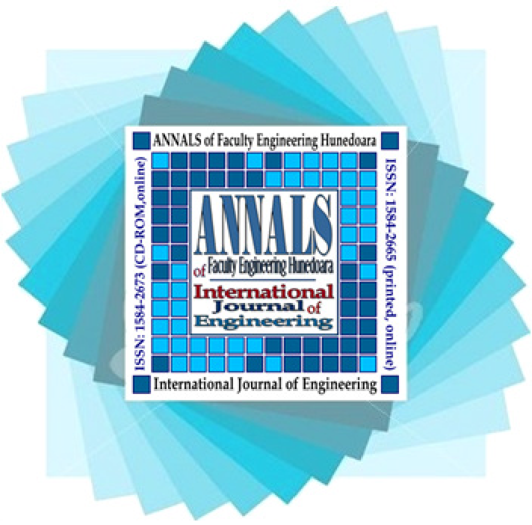

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