IN-SITU STUDY OF RECRYSTALLIZATION AND DEFORMATION PROCESSES IN FREE-CUTTING STEEL

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Abstract

An effect of static recrystallization with inclusion interaction and a change of tensile mechanical properties of drawn free-cutting steel has been studied in the scanning electron microscope (SEM) equipped with a combined in-situ heating and tensile stage. The main goal of all in-situ tests was to effectively improve plasticity and optimize strength which is important for application of the final products from free-cutting steels. The tests were performed on two types of cold-drawn free-cutting steels 11SMnPb30 and a lead-free variant 11SMnBi30. The rough square-shaped bars were delivered in high strength state (R_e = 607 MPa, R_m = 658 MPa) and low plasticity (A_5 = 10 %) and final fixing products. A series of electron backscattered diffraction (EBSD) mapping of selected area was used for monitoring of static recrystallization process [1-3] on in-situ heated sample from 450 up to 550 °C to provide information about structural changes. The original heavily-deformed structure with many dislocation sub-cells started the recovery process at 450°C and continued to a massive recrystallization at 550 °C. The influence of inclusions on all processes were studied as well. After sample cool down to the room temperature a tensile experiment was performed to compare the change of mechanical properties of the recrystallized sample to the original state of cold-drawn sample without any thermal treatment. A novel approach of multi-site in-situ deformation process monitoring has been used utilizing an advanced software integration and automation possibilities of a combined tensile-heating stage by NewTec and with TESCAN SEM image acquisition.

Keywords: In-situ, scanning electron microscopy, EBSD, materials testing

1. INTRODUCTION

Free machining steels are low carbon steels that have sulfur, phosphorus lead and as a dry lubricant element lead, bismuth, selenium or tellurium is added . Sulfur forms the compound manganese sulfide MnS, which is soft and acts as a chip-breaking discontinuity. It also acts as a dry lubricant to prevent a built up edge on the cutting tool.

In the last decade large research was done on development of nontoxic lead-free free-cutting low carbon steels characterized by excellent machinability and high hardness, high wear resistance and exceptional dimensional stability after hardening. One promising element in terms of replacement of toxic lead is (non-toxic) bismuth. Both elements are added due to their low melting point. During machining they melt and form a thin film of liquid for a fraction of a microsecond to lubricate the cut. Other advantages of bismuth include: more uniformly distribution because of its similar density to iron; more environment-friendly compared to lead; weldability.

For safe application of steel anchors made from free-cutting steel is necessary to know optimal recrystallization annealing conditions vs. required mechanical properties and corresponding deformation process. The main goal of all in-situ tests was to effectively improve plasticity and optimize strength which is important for application of the final products from free-cutting steels.

2. EXPERIMENTAL DETAILS

2.1. Materials

Flat specimens with geometry shown in **Figure 1a** had rectangular cross section of 3 mm x 2 mm and a gauge length of 6 mm. They were prepared by electro-erosion spark machining from cold-drawn square bars 10 mm x 10 mm of free-cutting steels 11SMnPb30 (1.0718) from WDI BlankStahl supplier and cold-drawn round bars D15 mm of free-cutting steels 11SMnBi30 from Třinec steelworks/Moravia supplier steel with chemical composition and mechanical properties are shown in **Table 1**. Specimen surface was carefully mechanically grinded/polished and final local polishing was done by Xe^+ ion beam on TESCAN FERA 3 FIB-SEM. The structure of both steels consists from ferrite grains and 10 % of pearlite. The MnS inclusions were classified as 1.1 type according to the standard SEP 1572. Lead and Bismuth element distribution are around the MnS inclusions (see **Figure 1**). The grain size of ferrite is very fine about 10 μm with small subgrains around 1-2 um (see **Figure 1b**) corresponding to the big deformation after cold-drawn.

Table 1 Chemical composition (in wt. %) and mechanical properties of both free-cutting steels

Steel/Element	C	Si	Mn	Pb	P	S	Bi	$R_{p0.2}$ (MPa)	R_m (MPa)	A_5 (%)
11SMnPb30	0.08	0.05	1.11	0.25	0.084	0.3	-	607	658	10.1
11SMnBi30	0.07	0.04	1.1	-	0.1	0.31	0.2	516	552	10.7

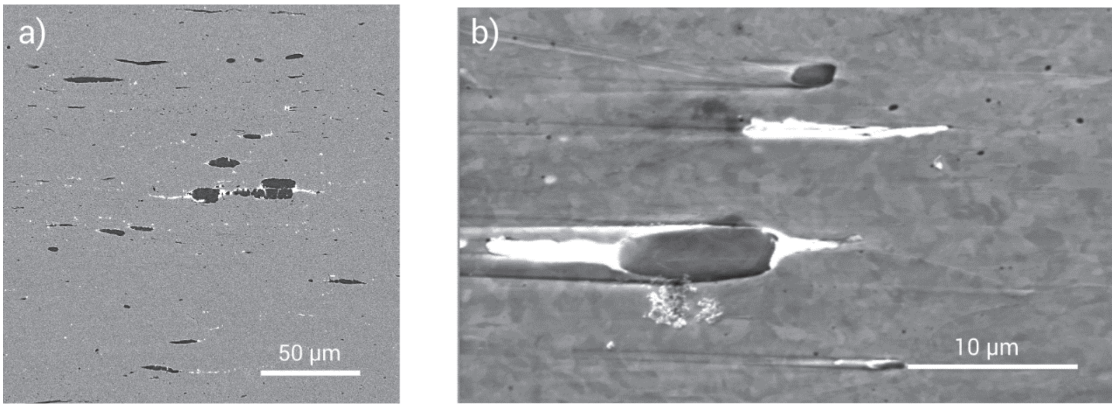

Figure 1 SEM BSE images of microstructure of (a) 11SMnPb30 steel and (b) 11SMnBi30 steel.

2.2. In situ experiment

The specimen was tested in-situ in the vacuum chamber of a scanning electron microscope TESCAN MIRA 3 with FEG cathode using tensile stage MT1000 by NewTec. The MT1000 is a fully automated tensile and heating stage for high resolution in-situ experiments (see **Figure 2b**). The tensile test was performed in displacement control mode with the traction speed of 2 μm/s at room temperature. The extension of jaws was measured by the extensometer mounted on the back side of the stage (**Figure 2**). During in-situ deformation SEM micrographs were taken automatically using the annular back-scatter electron (BSE) and secondary electron (SE) detectors. The stage software allows a fully automated systematic observation of nine selected locations distant approx. 1 mm along the sample (**Figure 3**). The images of all sites were taken after a fixed displacement interval of 50 um up to a final fracture (**Figure 3c**).

An in-situ heating test with temperature up to 550°C was done with the EBSD observation of the recrystallization process using Bruker e-Flash 1000 EBSD camera. After the heat treatment another in-situ tensile experiment was performed to obtain information about mechanical properties change connected to the structural changes from the recrystallization process

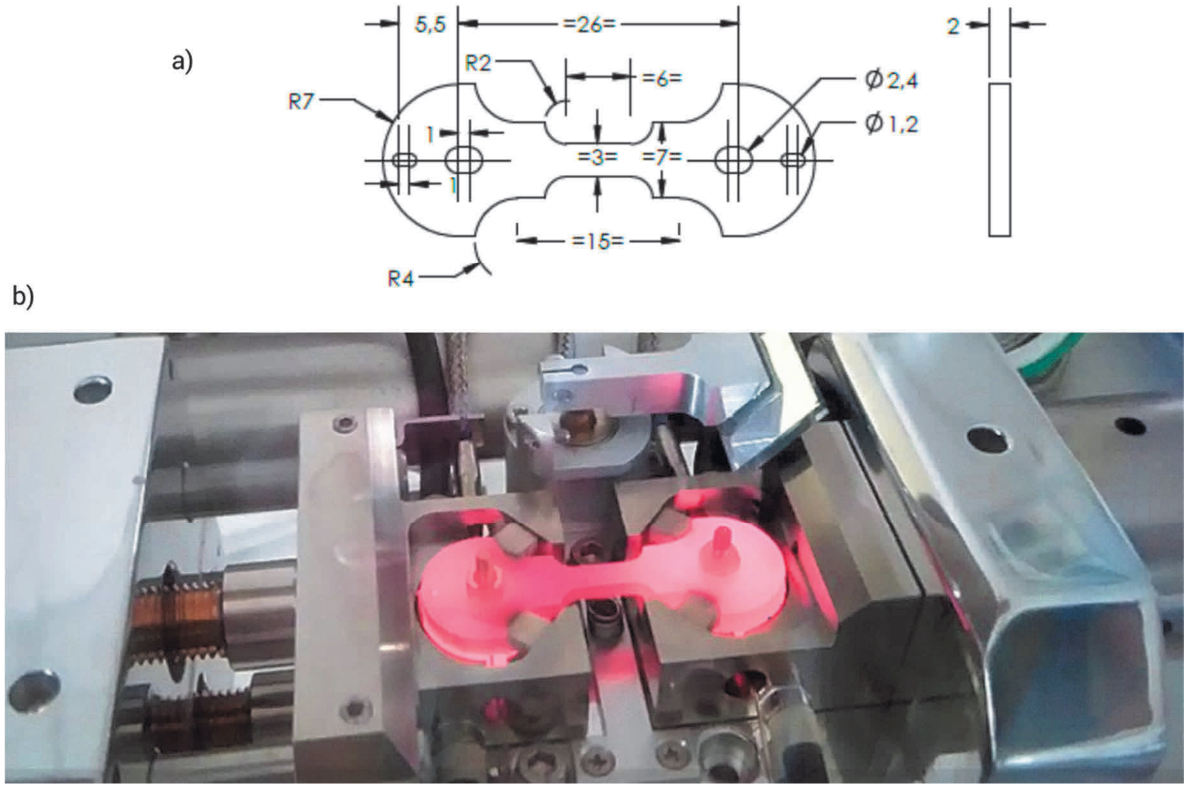

Figure 2 Specimen geometry for in-situ tests(a) and (b) tensile stage MT1000 NewTec

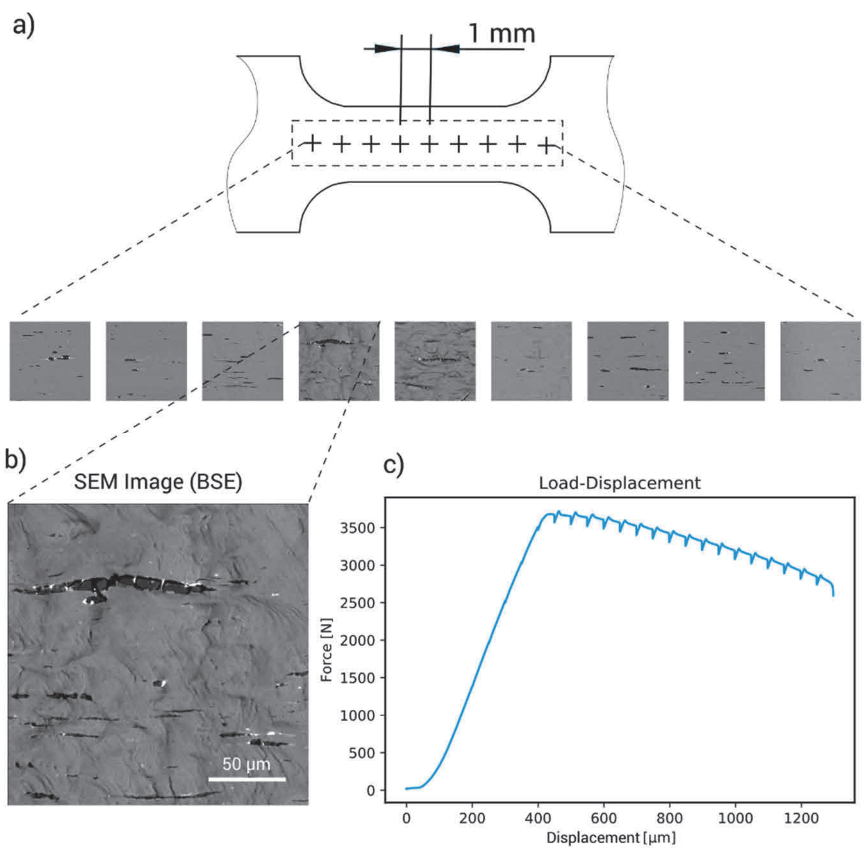

Figure 3 Multi-site in-situ experiment a) location of observation sites monitored during in-situ experiment, b) SEM image on location close to failure, last step, c) load-displacement diagram

3. RESULTS AND DISCUSION

The in-situ EBSD observation of the recrystallization process showed the first recrystallized grains were observed at about 480°C and followed by a massive recrystallization at 550°C (**Figure 4**). The in-situ tensile experiments after the heat treatment showed a rapid decrease of mechanical properties. (**Figure 5**).

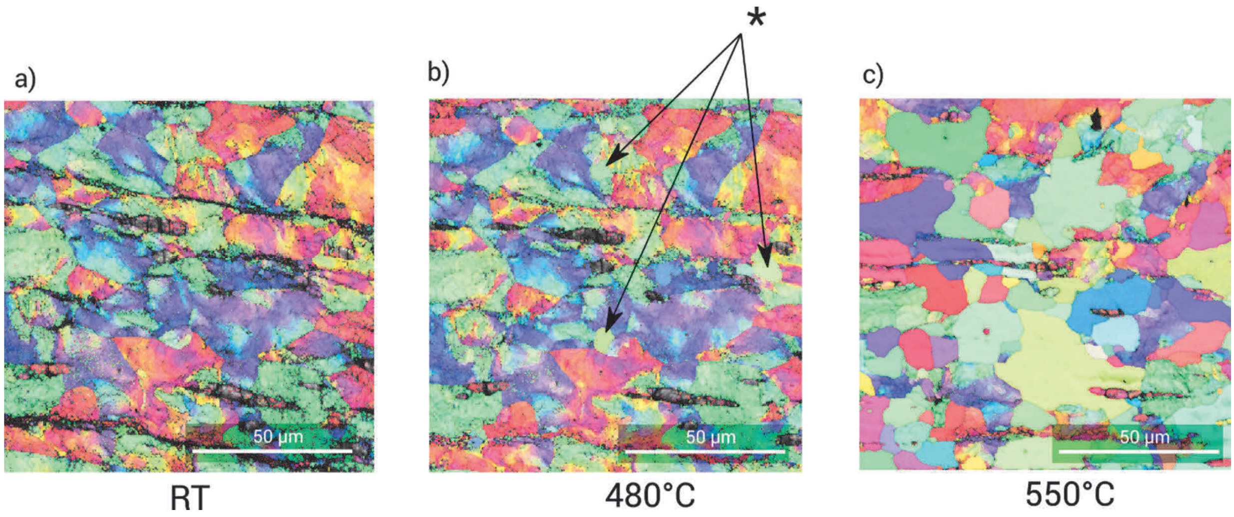

Figure 4 In-Situ EBSD recrystallization observation with increasing temperature a) initial drawn state at room temperature, b) recrystallization start at 480°C , *- new grains nuclei; c) massive recrystallization 15 min. at 550°C

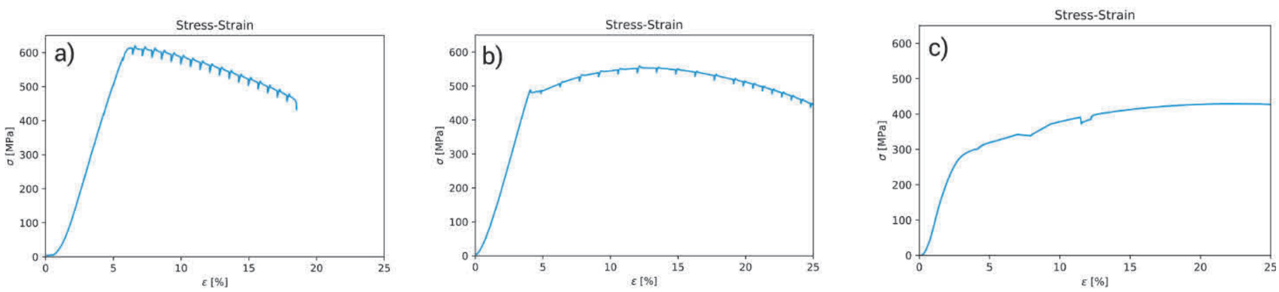

Figure 5 Tensile test results a) without thermal treatment (drawn state), b) after annealing to 480°C for 60 min., c) after 15min. at 550°C, test stopped when necking observed.

4. CONCLUSIONS

The experimental SEM in-situ recrystallization and deformation process and their analysis allow to draw following conclusions:

(i) Important details of the deformation mechanisms during tensile straining and recrystallization of free-cutting steel can be revealed by tensile/heating stage MT1000 NewTec equipped by multi-site in-situ deformation process monitoring and microscope TESCAN MIRA 3 FEG-SEM.

(ii) the effect of annealing/temperature on structure changes are recovery in sub grains regions up to 450 °C but main recrystallization process begins more intensive at 550 °C.

(iii) The original tensile properties of cold-drawn samples have necking with inclusion cracking immediately after elastic loading typical for steel with higher strength and low plasticity. Otherwise the steel after recrystallization at 480 °C/1hour is more plastic due to elastic-plastic region before necking with small reduction of tensile strength 70 MPa.

(iv) The influence of MnS inclusions on recrystallization is done by concentration of deformation by notch effect and play role as partial nucleation site for new grains.

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