

# FEM Modeling of Dynamic Recrystallization in 304 Stainless Steel

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## Abstract

Series of isothermal uniaxial compression tests in the temperature range (600-1100°C) with two strain rates of 0.1 and 1.0 s<sup>-1</sup> were performed with the aim to obtain input data for the finite elements modeling (FEM) of dynamic recrystallization (DRX) in 304 stainless steel. A symmetric behavior and microstructures were found, indicating that the maximum of calculated values for both plastic equivalent strain (PES) and plastic equivalent strain rate (PESR) were found to be in the center of the sample.

## Introduction

Trends in industry toward “zero tolerance” to errors in production and related expences, have imposed a need for a reliable modeling. Intensive development and low cost of computers have enabled FEM to gain a very important position [1]. During deformation at high temperatures two different processes occur simultaneously [2,3]: (i) work hardening due to an increase of dislocation density, and (ii) softening due to a restoration processes (recovery and recrystallization). The aim of this paper is to explain the dynamic recrystallization (DRX) process in SUS304 stainless steel under the severe plastic deformation at high temperatures, and to give finite elements modeling (FEM) image of plastic equivalent strain (PES) and plastic equivalent strain rate (RESR) for the compressed sample.

## Experimental

Chemical composition of the SUS304 stainless steel tested in this work is given in Table 1.

Table 1. *Chemical composition of SUS304 (in wt.%)*

	C	Si	Mn	P	S	Ni	Cr	Cu	Mo	V	Al	Ti
SUS304	0.049	0.3	1.14	0.035	0.025	9.96	18.06	0.39	0.3	0.07	<0.005	<0.01

Uniaxial compression tests were done on a thermomechanical treatment simulator, THERMECMASTOR-Z. Steel was tested at five different temperatures, i.e. 600, 750, 900, 1000 and 1100°C, and applying two strain rates 0.1 and 1.0 s<sup>-1</sup>. The reduction of samples

height was up to 75%. Metallographic analysis of both non-compressed (only heated) and compressed samples were conducted using optical microscope. To provide accurate information on the grain size at high temperature samples were quenched by helium gas. Grain size of both non-compressed and compressed samples was measured and compared using a circumference method.

FEM analysis was used for calculation of PES and PESR in the central position of samples. This analysis was performed by ABAQUS computer program.

## Results and Discussion

**True Stress-True Strain Curves.** Load–displacement curves from uniaxial compression test were calculated to true stress-true strain curves. Typical true stress-true strain curves are presented in Fig. 1.

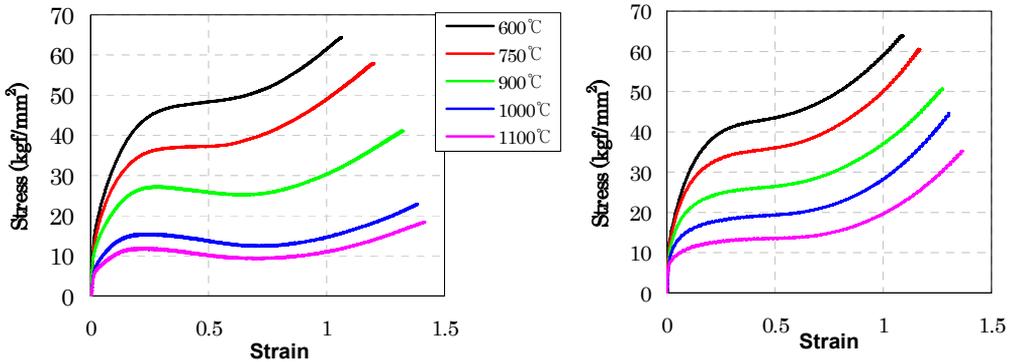


Fig. 1. True stress-true strain curve at strain rate of  $0.1$  and  $1.0 \text{ s}^{-1}$

With increase of strain, stress increases at a constant slope. At one point the rate of hardening starts to decrease, i.e. nucleation of dynamic recrystallization occurs. With further increase of strain, stress rises up to the local maximum, which is followed by the decrease of stress, i.e. DRX has prevailed over strengthening. This behavior continues up to the point when DRX is completed. Further increase in strain is followed by an increase in stress, due to barreling effect. Therefore, it was concluded that SUS304 austenitic stainless steel shows a typical DRX behavior [2]. However those curves show that at the equal strain rates load decreases with an increase in temperature (load exhibits the maximum value at the lowest temperature of  $600^\circ\text{C}$ ).

General observation of curves shows that stress decreases with an increase of temperature; the resistance to the plastic deformation of the material decreases with increase of temperature. Different shapes of curves may be seen at  $600^\circ\text{C}$ . It was concluded that the work hardening process at  $600^\circ\text{C}$  has prevailed over the softening mechanism. Also, the peak stress decreases with increase of test temperature.

**Metallographic Analysis.** Typical microstructure at  $1100^\circ\text{C}$  of a non-compressed sample is shown in Fig. 2. Grain size of non-deformed samples at different temperatures are given in Table 2. The initial grain sizes of all samples have similar values, indicating that heat treatment temperatures did not cause major effect on the grain size.

Fully recrystallized microstructure was found in samples deformed at  $1100^\circ\text{C}$  with strain rate of both  $0.1$  and  $1.0 \text{ s}^{-1}$ . Summary of DRX occurrence is given in Table 3. Occurrence of DRX was evaluated using optical microscope. DRX grains are very small,

sometimes even for an order of magnitude in comparison to prior grains. Therefore, presence of small grains was attributed to DRX structure.

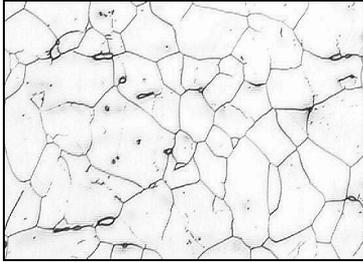


Fig. 2. Microstructures of the heated specimens (central position, 1100°C, x100)

Table 2. Grain size of the non-deformed specimens

T °C	grain size (μm)
600	47.8 ± 1.970
750	41.9 ± 0.690
900	41.1 ± 1.644
1000	42.0 ± 0.689
1100	40.4 ± 0.869

Optical microscopy (magnification x1000) was performed to investigate the DRX behavior at higher temperature (900°C). A typical partial DRX was found at 900°C. Optical micrographs show a presence of initial very large grains that may be noticed by bright (white) color.

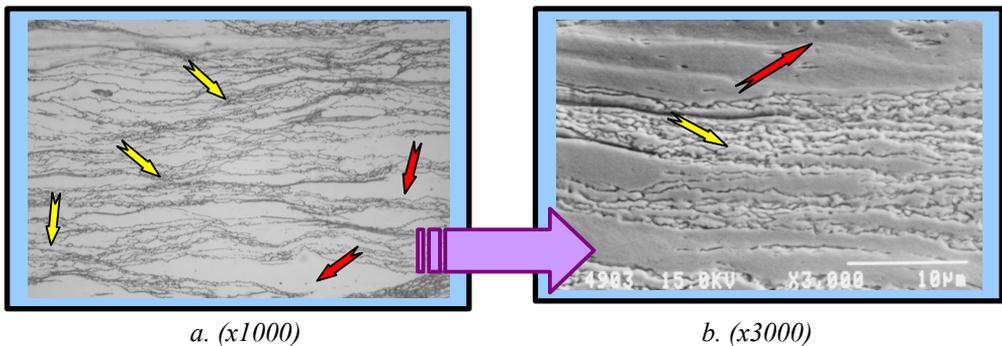


Fig. 3. Optical(a) and SEM (b) micrographs of specimens at 900°C (strain rate 1.0 s<sup>-1</sup>)

Table 3. Summary of DRX behavior

strain rate (s <sup>-1</sup> )	Temperature (°C)	DRX behavior
0.1	600	no DRX
	750	no DRX
	900	partial DRX
	1000	complete DRX
	1100	complete DRX
1.0	600	no DRX
	750	no DRX
	900	partial DRX
	1000	partial DRX
	1100	complete DRX

Table 4. Grain sizes of the marked positions 1000°C (strain rate 0.1 s<sup>-1</sup>)

position	grain size (mm)
P15	32.5 ± 1.296
P9	12.5 ± 0.559
P4	7.8 ± 0.351
P0	5.9 ± 0.222
P-4	7.8 ± 0.342
P-9	13.7 ± 0.508
P-15	23.7 ± 0.409

On the other side, dark (black) areas belong to groups of a newly formed recrystallized grains. SEM results confirmed this fact presenting a clearer image of this behavior. This leads to conclusion that the material starts to recrystallize around 900°C. Fig. 3 shows a typical (partially recrystallized?) DRX structure with yellow arrows pointing to recrystallized grains and red arrows indicating initial (non-recrystallized) grains. It was also expected that the complete DRX might have occurred at higher temperatures. For further analysis, specimen deformed with  $0.1 \text{ s}^{-1}$  strain rate at 1000°C was chosen. This specimen was cut at the half and the surface was observed at basically four positions. Sketch of the sample and positions of the marked places is shown at Figure 4.

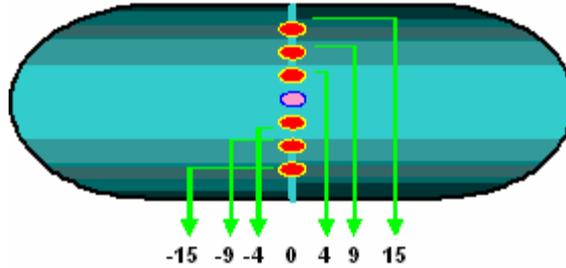


Fig. 4. Sketch of the compressed sample with marking points

The first step of the investigation was to obtain the grain size at each of the chosen position. Results illustrated in Table 4 and in Fig. 5 show interesting behavior of the material: largest grains are closer to edge, and grains are becoming smaller towards the center of the specimen. Similarity in the grain size from both sides of the specimen was obtained, but the edge positions (15 and -15) somehow differ from each other. It was assumed that cooling with helium was not quite uniform.

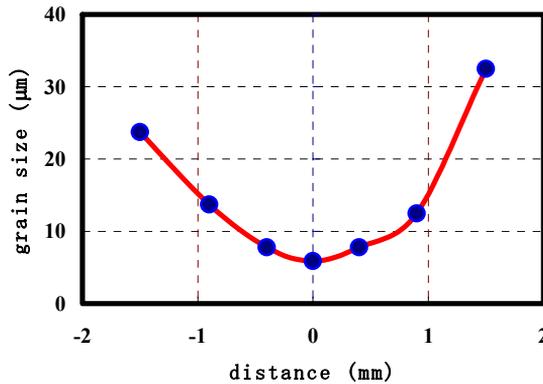


Fig. 5. The dependence of grain size from the distance at marked positions

The purpose of this analysis was to understand the mechanism of DRX, at a constant strain rate and temperature. Microstructures of marked positions are shown in Fig. 6. Grains were large and no DRX occurred at edge positions, while positions P-9 and P 9 (referred as  $\pm 0.9\text{mm}$  distance) show a typical behavior of this material. In these areas old initial larger grains are present among new smaller grains showing that DRX started but was only partially completed. Partial recrystallization is still present in the zone up to approximately 0.3mm from the center. Therefore, in positions P-4 and P 4 (referred as  $\pm 0.4\text{mm}$  distance)

two different types of grains may still be distinguished. At the central position (P 0) only one type of grains was present suggesting that DRX was completed in this case.

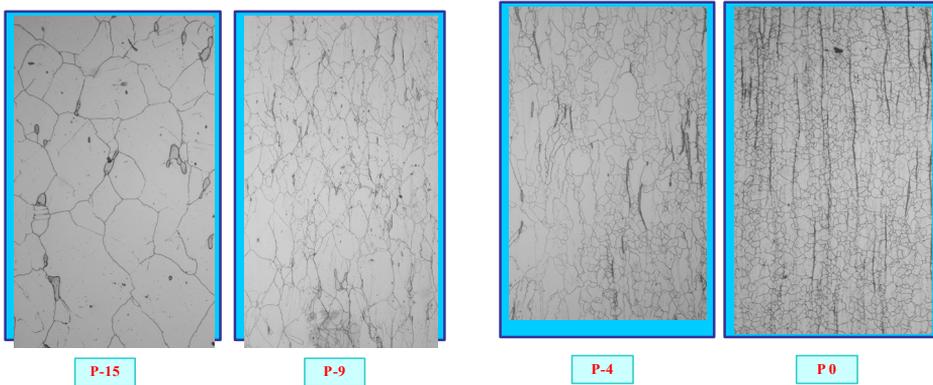


Fig. 6. Microstructure of the marked positions  $\times 400$

**FEM Analysis.** FEM analysis was used to evaluate the plastic equivalent strain distribution inside the samples introduced by the deformation. The model was defined as linear axisymmetric solid element with four nodes. PES and PESR were calculated from FEM and the highest PES was found in the center of the specimens. The maximum value was obtained for the 73% compressed sample at  $1100^{\circ}\text{C}$  and  $0.1\text{ s}^{-1}$  strain rate. However, it was detected that PES was increasing with an increase of temperature at the constant strain rate. The smallest grain size ( $3.3\mu\text{m}$ ) was found at  $1100^{\circ}\text{C}$  and strain rate of  $1.0\text{ s}^{-1}$ .

PES distribution obtained by FEM, for one specimen deformed at  $1000^{\circ}\text{C}$  and  $0.1\text{ s}^{-1}$  strain rate is shown in Fig. 7. This 2D image shows a half of the surface of compressed sample. Blue and red areas represent the lowest and the highest PES distribution, respectively. The highest PES (3.587) was detected at central position of the specimen ( $1100^{\circ}\text{C}$ ,  $0.1\text{ s}^{-1}$ ). From this FEM image it was confirmed that the highest PES was in the center of the sample. However, one large area around the center of the top edge, known as a “dead metal zone”, was not deformed. PESR distribution was found to be similar to PES distribution behavior. Highest values of PES are in good agreement with the calculated PESR values.

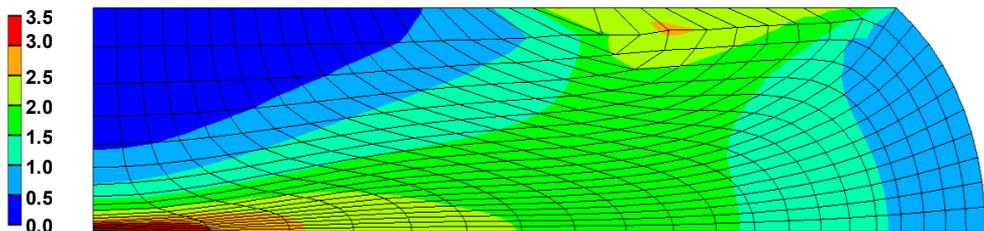


Fig. 7. PES distribution (height reduction: 71.6%)

### Conclusions

Ultrafine grains were formed due to dynamic recrystallization. Complete DRX was obtained at the highest testing temperatures ( $1000^{\circ}\text{C}$  and  $1100^{\circ}\text{C}$ ). The smallest grain size ( $3.3\mu\text{m}$ ) was found at  $1100^{\circ}\text{C}$  and strain rate of  $1.0\text{ s}^{-1}$ . The highest PES (3.587) was detected by FEM at central position of the specimen ( $1100^{\circ}\text{C}$ ,  $0.1\text{ s}^{-1}$ ). Symmetric DRX

behavior and microstructure were found (at the both sides from the center) of the compressed specimen.

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