Effect of pre-strain on mechanical properties and deformation induced transformation of 304 stainless steel

Fahri R Zulfi and Akhmad A Korda

Department of Metallurgical Engineering, Faculty of Mining and Petroleum Engineering, Bandung Institute of Technology, Jl. Ganesha 10 Bandung 40132, Indonesia

E-mail: akhmad@mining.itb.ac.id

Abstract. Effect of pre-strain on mechanical properties and deformation induced phase transformation of 304 stainless steel under tensile deformation has been studied. Pre-strain with the variation percentage of deformation was applied to the tensile test specimens. Tensile and hardness testing were carried out after pre-strain to study the mechanical properties change. Deformation induced phase transformation was investigated by using X-ray diffraction and optical microscope. XRD study indicates that metastable austenite transforms to martensite due to deformation. The martensite volume fraction increases with the increase in percentage of deformation. The increase in strength and hardness were associated with an increase in the volume fraction of martensite.

1. Introduction

Austenitic stainless steel are used in many application require severe deformation because their high ductility. Austenitic stainless steels divided into various series with different characteristics, the most popular series are 304stainless steel [1-3]. It cannot be hardened by heat treatment, but soft austenitic structure from annealed condition will transform to martensite during deformation. The martensite is stronger and harder than austenite, combination between these two phases resulting good combination of strength, formability, ductility, and corrosion resistance [4-6]. It is known that deformation induced transformation increase strength, but decrease the toughness also stainless steels processability. The volume fraction of particular phase also influences another properties such as corrosion resistance and magnetic properties. The degree of martensite deformation depends on chemical composition, cold working parameter, strain rate, and mode of deformation [7].

In this study, the effect of deformation induced transformation in 304 stainless steel was investigated for tensile test specimen in various pre-strain conditions. Mechanical properties change was investigated associated with volume fraction of martensite changes due to deformation induced transformation [8]. Phase transformation of specimen was studied by microstructure observation and x-ray diffraction analysis. Relation between deformation alongside break tensile test specimen were investigated for discussing the transformation microstructure and mechanical properties during tensile test.

2. Experimental Procedures

The material employed in this study was cold rolled 304 stainless steel plate. The chemical composition and mechanical properties of the 304 stainless steel plate are shown in Table 1 and 2, respectively. Figure 1 shows the austenitic microstructure of the SS 304 in annealed condition. The

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

tensile test specimen for the steel plates have a gage length of 50 mm, a width of 12.5 mm and 7 mm thick as shown in figure 2. The specimens were plastically deformed at various % pre-strain with strain rate of 0.02/sec. Dimension of the tensile test specimen along the gage length were measured before and after pre-strain. Pre tensile strain was applied to the specimen by using a universal tensile machine with a tensile strain at 14, 26, 42 and 52%. After the pre-strain, the specimens were then pulled until breaking to investigate the changes in mechanical properties such as yield strength, tensile strength and elongation. The hardness before and after the pre-strain was also measured using a Vickers microhardness tester. Hardness testing and microstructure observation were also conducted along the broken specimens, in an area far and near to the fracture. Microstructure observation conducted on polished and etched specimens. The specimens for metallographic observation, microhardness and X-ray diffraction were taken and prepared by wire cutting from the gage length area after the pre-strain.

Table 1. Chemical composition of the SS304 (%wt)

C	Cr	Ni	Si	N	Fe
0.08	18.08	8.10	0.75	0.10	bal.

Table 2. Mechanical properties of the SS304 plate

Properties	Measured values
Tensile Strength (MPa)	586
Yield Strength (MPa)	241
Hardness (HV)	173

Figure 1. Microstructure of the cold rolled 304 stainless steel used in this study

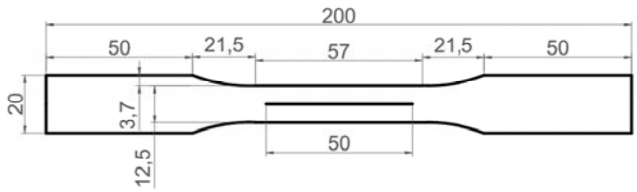

Figure 2. Tensile test specimen (in mm)

Phase analysis was carried out using Philips Analytical with PC-APD diffraction software equipped with Cu radiation anode tube. It was supplied with current intensity of 30 mA and the voltage of 40 kV. The wavelength of Cu radiation was 1.5406 angstrom with continuous scanning and step size of 0.02°. The obtained diffraction patterns were analyzed using X-Powder software. Quantitative phase of volume fraction martensite was calculated by Averbach-Cohen Method [9].

3. Result and Discussions

Figure 3 shows microstructure of the investigated SS304 plate after tensile pre-strained at 14, 26, 42 and 52%. The structure of deformed SS 304 is characterized by slip bands and deformation twins of austenite grains. The slip bands and the deformation twins appear to be more evident as the deformation increase. It is also seen in the figure that the dark region of martensite is observed to be more pronounce than that of the light areas of austenite as the pre-strain increase from 14% to 52%.

Figure 4 shows the X-ray diffraction pattern for the investigated SS 304 plate at various tensile pre-strain. From the figure it can be seen the reflected peaks of γ and α' phase. For as received SS 304 plate, the reflected lines of (111), (200), (220) and (311) planes of the austenite phase and reflected line of (101) plane of the martensite phase were observed.

Journal of Physics: Conference Series **739** (2016) 012039 doi:10.1088/1742-6596/739/1/012039

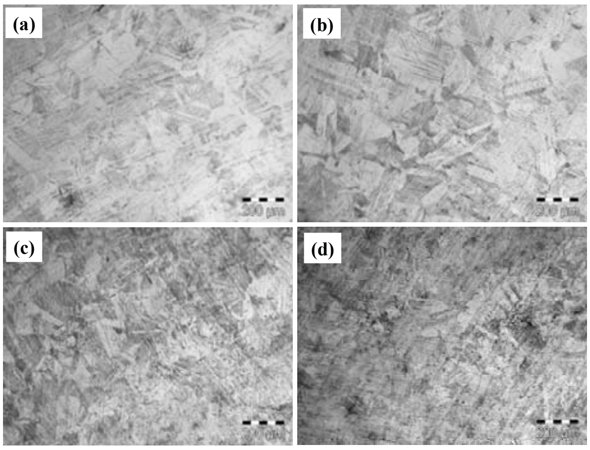

Figure 3.Microstructure of investigated SS304 after deformation (a) 14% pre-strained, (b) 26% pre-strained, (c) 42% pre-strained, (d) 52% pre-strained. Light etching phase—austenite; dark—martensite

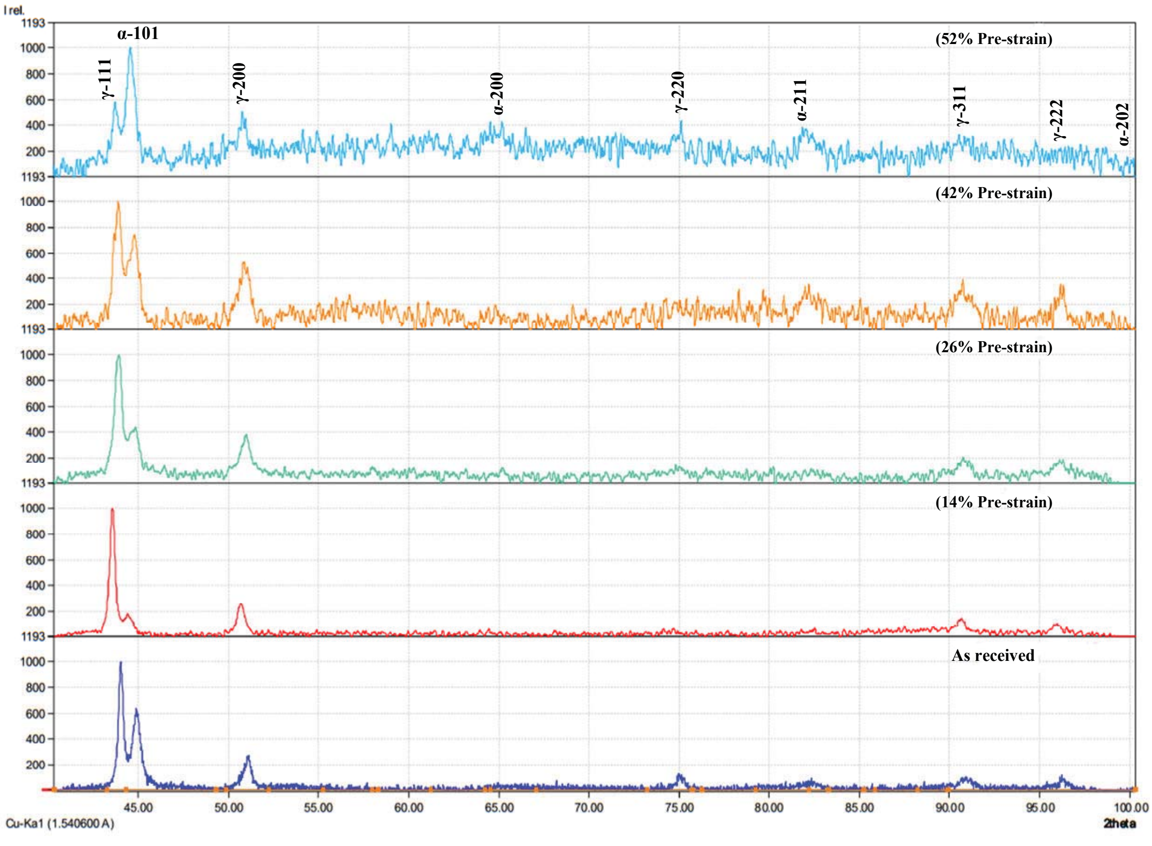

Figure 4. Diffractograms for the SS304 plate at various tensile pre-strain

Increase in pre-strain was found to decrease the relative intensity of the (111), (200), (220) and (311) planes of γ. On the other hand, the increasing percent of pre-strain strengthen the reflected lines of (101), (200) and (211) planes of α' phase. The presence of in the α' phase diffraction patterns and

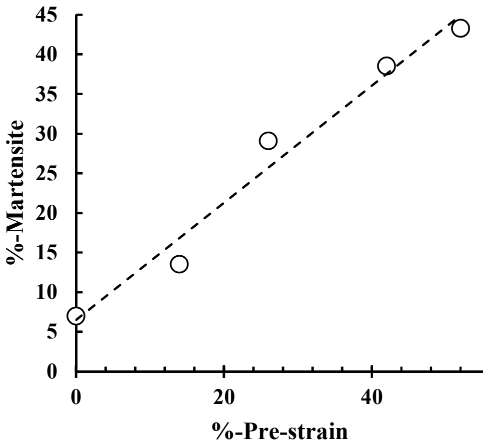

Figure 5. Martensite volume fraction of investigated SS304 plate in various pre-strained condition

an increase of their relative intensities indicate that the phase transformation of the γ to α' phase was taken place.

Using Averbach-Cohen method, phase analysis is carried out to see the changes in the martensite volume fraction due to increased pre-strain. Figure 5 shows the results of α' phase calculation. From the figure, it is shown that the increasing pre-strain will increase the volume fraction of martensite. Percent volume of martensite increased from 7% for the as received condition to 43% on the condition of the 52% pre-strain. Phase transformation from γ to α' as a result of the pre-strain would change the mechanical properties of the investigated SS 304 plate.

As indicated by Kurc and Stoklosa [1], volume fraction of martensite also increase due to cold rolling deformation proportionally.

Volume fraction of martensite from tensile pre-strain is higher than cold rolling in same degree of plastic deformation because tension stress is more beneficial for martensite formation than compression [5].

Figure 6 shows stress-strain curve of the investigated SS 304 plate at various tensile pre-strain. The curve shows that the mechanical properties of tensile strength, yield strength and elongation change after pre-strain at different percentages. It is also seen that the slope of the work hardening area tends to decrease with increasing pre-strain. The results of tensile and hardness test of the steel are summarized in figure 7 and 8. Figure 7 shows the change of tensile strength and yield strength of the investigated steel plate after pre-strain. In the figure it can be seen that the strength increases with the increasing pre-strain. The difference between the tensile strength and yield strength also decreases with the increasing percentage of the pre-strain. The tensile strength of the SS 304 plate increase from 599 MPa (as received) to 919 MPa (52% pre-strain).

The yield strength of the steel plate increase from 289 MPa (for as received) to 872 MPa after a pre-strain of 52%. Figure 8 shows the relationship between elongation and hardness of the investigated steel plate at different percentages of pre-strain. It is seen that the elongation decreased with increasing pre-strain. The steel elongation decreases from 73% (as received) to 33% (52% pre-strain).

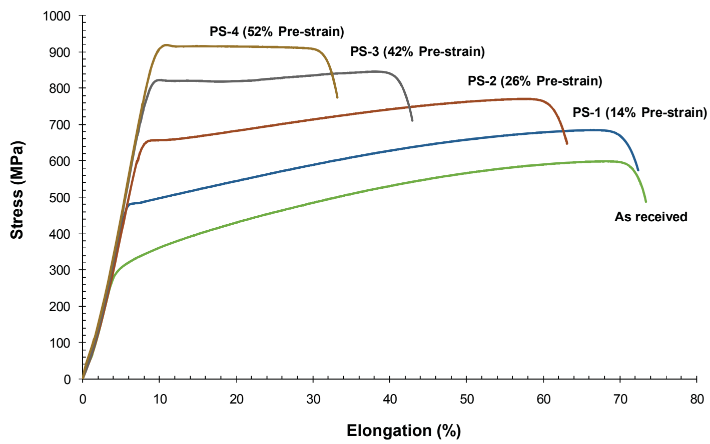

Figure 6. Stress-strain curves for the 304 stainless steel in various pre-strain conditions

Meanwhile the hardness of the investigated SS 304 plate increased to 406 HV (52% pre-strain) from as received value of 181 HV. The increase in strength and hardness occur as a result of the increasing α' phase with the increasing pre-strain.

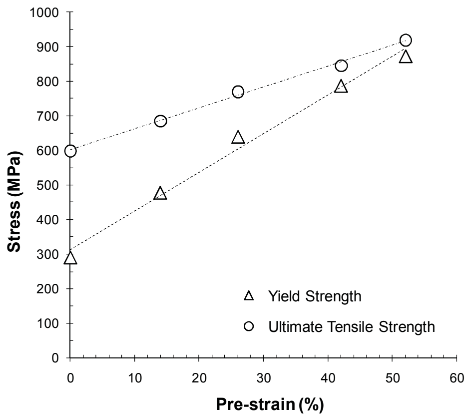

Figure7. Strength of SS 304 plate at various tensile pre-strained condition

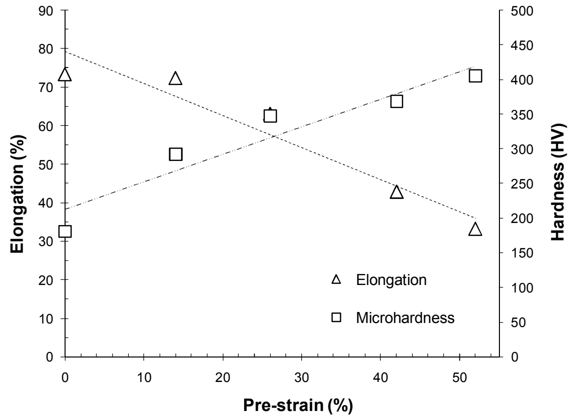

Figure 8. Elongation and hardness of SS304 plate at various tensile pre-strain

To study the changes in the microstructure and mechanical properties, especially hardness at a high level of pre-strain as in a condition close to broken, then the metallographic and hardness testing is done along the tensile test specimens which had been fractured. Figures 9 and 10 respectively show hardness value along break part of tensile test specimen after pre-strained 52% and microstructure observed along break part of tensile specimen at various distance from breaking area. The microstructures observed at distances of 70, 55, 30, 15 and 5 mm from the fracture area.

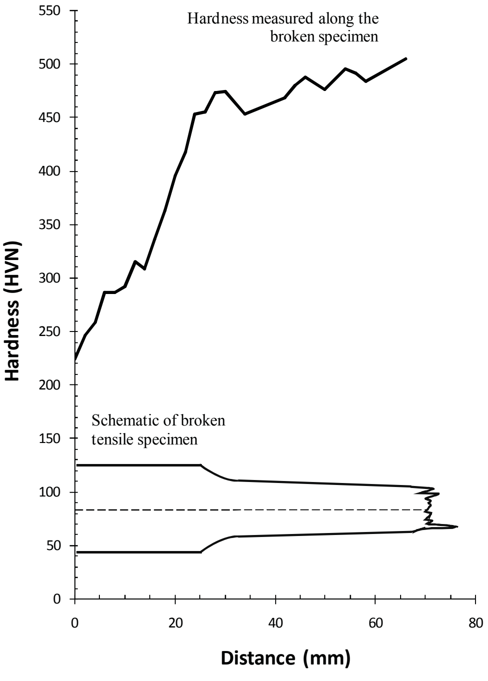

Figure 9. Hardness value along break part of tensile test specimen after pre-strained 52%

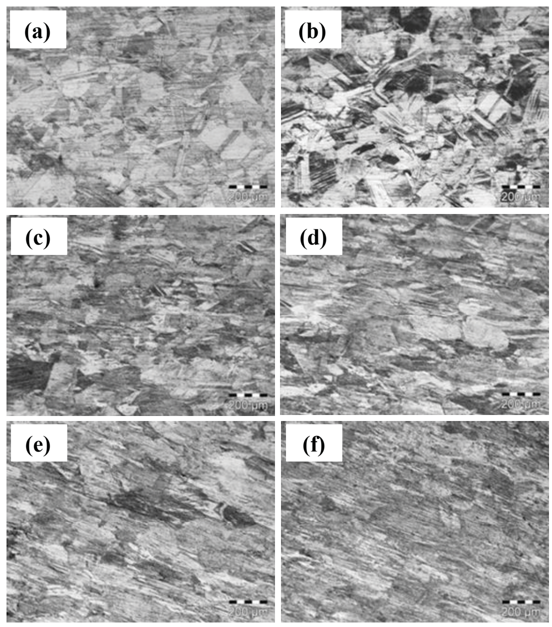

Figure 10. Microstructure observed along break part of tensile specimen at various distance from breaking area, (a) 70 mm, (b) 55 mm (c) 30 mm, (d) 15 mm, (e) 5 mm, (f) at break. Light etching phase-austenite; dark-martensite.

The results show that an increase in hardness towards the fracture area. Previous specimens have a hardness of 450 HV at the pre-strain of 52%. Approaching the fracture area, this hardness continues to increase to nearly 500 HV. As well as hardness, microstructure changes are evident, especially when observed from a considerable distance from the fracture area to nearly to the fracture area. From the observation it can be seen that the microstructure changes from low tensile deformation level to a high tensile deformation level. In areas near fracture, the grains seem to experience severe deformation level so it is difficult to be observed clearly.

4. Conclusions

Deformation induced transformation investigation were carried out to 304 stainless steel plate with various tensile pre-strain. The x-ray diffraction analysis showed that the change of the γ phase into α' phase due to cold deformation. Total volume fraction of martensite depends on the degree of plastic deformation. Percent volume of martensite increased from 7% for the as received condition to 43% on the condition of the 52% pre-strain. Phase transformation from γ to α' as a result of the pre-strain would change the mechanical properties of the investigated SS 304 plate. Increase in the volume fraction of martensite causes an increase in strength and hardness and elongation decrease.

References

[1] Kurc A and Stoklosa Z 2008 *Archives of Materials Science and Engineering* **34** 2 pp 89-94
[2] Karjalainen L P, Taulavuori T and Kyrolainen A 2008 *Steel Research International* **79** pp 404-12
[3] Kurc-Lisiecka A, Ozgowicz W, Ratuszek W and Chruściel K 2012 *Journal of Achievements in Materials and Manufacturing Engineering* **52** 1 pp 22-30
[4] Zhou S, Xue Z-y and Wei X-c 2010 *Journal of Iron and Steel Research* **17** 3 pp 51-55
[5] Hedstorm P 2007 *Proc. Of International Symposium on Steel Science (Kyoto)* vol 1 (The Iron and Steel Institute of Japan) pp 171-174
[6] Ishimaru E, Hamasaki H and Yoshida F 2014 *Procedia Engineering* **81** 9 pp 21-26
[7] Osgowicz W, Kurc A and Kciuk M 2010 *Archives of Materials Science and Engineering* **43** pp 42-53
[8] Takahashi S, Echigoya J and Ueda T 2001 *J. of Materials Processing Technology* **108** pp 213-216
[9] Cullity B. D 1978 *Elements of X-Ray Diffraction* 2^{nd} (Philippines: Addison-Wesley Publishing)