Effect of Cold Working on Hardness and Strength Properties of 316 Austenitic Stainless Steel

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الملخص

الهدف من هذا البحث دراسة تأثير التصليد الانفعالي على الخواص الميكانيكية لسبيكة 316 ستانلس ستيل. التشكيل على البارد تم عن طريق ألة شد بنسب 20%, 40% تشكيل على البارد متبوعا بمعالجة حرارية للتخلص من الإجهادات الداخلية. دورة ثانية من التشكيل على البارد تم إجراؤها للعينات المعالجة حراريا متبوعة بعملية معالجة حرارية ثانية. قياسات صلادة بمقياس روكويل والتركيب المجهري للمعدن تم عملها لكل العينات. لوحظ أنه كلما زادت نسبة التشكيل على البارد كل من الصلادة و مقاومة المعدن تزداد. من ناحية أخرى فإن اللدونة تنخفض. إختبارات التركيب المجهري أظهرت زيادة في طور المارتنسايت مع زيادة نسبة التشكيل على البارد.

Abstract

The objective of this research was to study the effect of strain hardening on mechanical properties of 316 austenitic stainless steel (ASS). Cold deformation was performed by using a universal tensile machine for 20% CW and 40% CW followed by heat treatment to relieve internal stresses. A secondary cold working was performed for the heat-treated samples followed by a secondary heat treatment. Rockwell hardness measurements and microscopic examinations were preformed for all samples. It was observed that by increasing the amount of CW%, both hardness and strength were increased. On the other hand, the ductility was decreased. The

microstructure examinations showed an increase in the martensitic phase by increasing the cold working of the material.

Key Words: Rockwell Hardness, Strain Hardening, 316 ASS, Cold Working, Ductility, Martensitic Phase, Stacking Fault Energy

Introduction

Deming Xu et al.[1] studied the effect of cold deformation (ranged between 0 and 40%) on the microstructure and mechanical properties of 316LN ASS. It was concluded that the content of martensite increased in the microstructure as the cold working increased. Also, the strength was increase while the ductility decreased. In another study, the effect of strain hardening on mechanical properties of S30408 austenitic stainless steel which is used in pressure vessels was investigated (Bo Li et al[2]). It was found that excessive plastic deformation can cause lower performance of vessels and may not meet the safety requirements because the decrease of the plasticity index contributes to the increase in the ratio of hard and brittle martensite phase.

The effects of strain hardening on the mechanical behavior of 316L stainless steel were studied by Kaishang Li et al[3]. The results demonstrate that the yield strength increases with the magnitude of strain hardening significantly (by using a strain hardening ranged between 0 and 10%), but the ultimate strength of the original and different strain hardening materials are closed which is not in agreement to the results of others[1,2]. It was found that both the fracture elongation and fracture surface shrinkage decreased with the magnitude of strain hardening. It is also concluded that the Ramberg-Osgood equation is used to predict the stress-strain curves after strain hardening, and the results indicate that the predicted values agree with the experimental values.

S. Tanhaei et al[4] evaluated the effect of different levels of cold rolling (ranged between 0 and 50%) on the microstructural and

mechanical properties of the 316L austenitic stainless steel. Mechanical properties determined by both tensile and Vickers microhardness tests in this study which demonstrated an upward trend in the hardness-to-yield strength ratio with increasing cold-rolling percentage, representing a reduction in the material's work-hardening ability. Uğur Özdemir et al[5] investigated the effect of the cold work hardening behavior of AISI 304 austenitic stainless steel and it was found that the hardness of this stainless steel is increased by cold deformation drastically. Also, it was found that by increasing the stress applied in the tensile test, microvoids on the grain boundaries were clearly detected in the microstructure.
Ali Hedayatu et al[6] investigated the effect of different reductions of cold rolling on the microstructure and mechanical properties were performed on the AISI 304L austenitic Stainless Steel by applying cold work ranging between 0% and 90% at 0 ^{o}C. It was found that X ray diffraction shows a formation of martensite phase which is increased by increasing the cold working percent. By increasing the cold working to 70%, the volume of martensitic phase was about 95% of the total volume of the microstructure, and at 90% cold working it reaches to 100% martensitic structure.
Hsin Shen Ho et al[7] states that the deformation induced martensite (DIM) can be formed after the strain hardening process of austenitic stainless steel which usually depends on the chemical composition of the steel and the cold working variables.
Angelo Fernando Padilha et al[8] concluded that by the addition of alloying elements significantly lowers the stacking fault energy (SFE) where screw dislocations cannot cross-slip across the low stacking faults, even under high stresses. Deformation twinning is dependant on the SEF and the grain size. The SFE for stainless steels can be calculated by the following equation:
SFE (mJ/m ^{2}) =-53+6.2(%Ni) +0.7(%Cr) +3.2(%Mn) +9.3(%Mo). (eq1)
The value of SFE of 316 stainless steels was ranged between 36 and 80 mJ/m^2 which is the highest value among the other austenitic stainless steels.
Based on the conflict in results for the previous studies, it was decided to study the effect of cold working on hardness, tensile

strength, yield strength and phase transformation for a 316 austenitic stainless steel.

Experimental Work

Commercial 316 Austenitic Stainless Steel (ASS) was used in this study. The chemical analysis of 316 ASS was determined by using the Atomic Absorption Spectrometer by others (Hala et, al[9]).
All samples were cut using a diamond saw into tensile test standard dimensions (per US specifications ASTM-E8 from ASS sheet) which were approximately (85 mm in gage length, 12.67 mm in width, 4.96 mm in thickness and 12.5 mm for the radius of fillet). Samples were subjected to pre cold working (20%CW and 40%CW), and some of these samples were subjected to a secondary cold working process by straining these samples to 20%CW (for the pre- 20% CW samples) and 40%CW (for the pre-40%CW samples). The pre-cold worked samples were heat treated by heating samples to 800 ^{0}C for 1 hour, then cooling them to room temperature in an electric furnace to relieve most of the stored internal stresses which formed due to the cold working process. Also, the secondary cold worked samples were heated to 600 ^{0}C for an hour, and then cooled in the furnace to room temperature for the same purpose. A Rockwell hardness (HRC) test by using a conical load of 150 Kg for all samples was performed at room temperature according to relevant standards. Surfaces of all samples were prepared for microstructure examination by ground samples using 240, 320, 400, 800, and 1200 grit SiC Papers, and polished using 1 micron alumina suspensions, followed by immersion in etching solution bath (5 ml of glycerol, 15 ml of HCl and 10 ml of Nitric acid) for 15 minutes. The microstructure of all samples was examined by using an optical microscope to find the effect of the cold working process on the microstructure.

Results and Discussion

Table 1 shows the chemical analysis of the 316 stainless steel that was used in this investigation.

Table 1 shows the chemical analysis of the 316 stainless steel

Element	Cr	Ni	Mn	C	Si	P	Mo	Fe
Wt%	16.2	13.0	2.00	0.07	0.71	0.043	2.00	Balance

All the hardness values were measured after performing the heat treatment for the strain hardening samples. The hardness values for the received sample, and samples with different cold work conditions shown in figure 1.

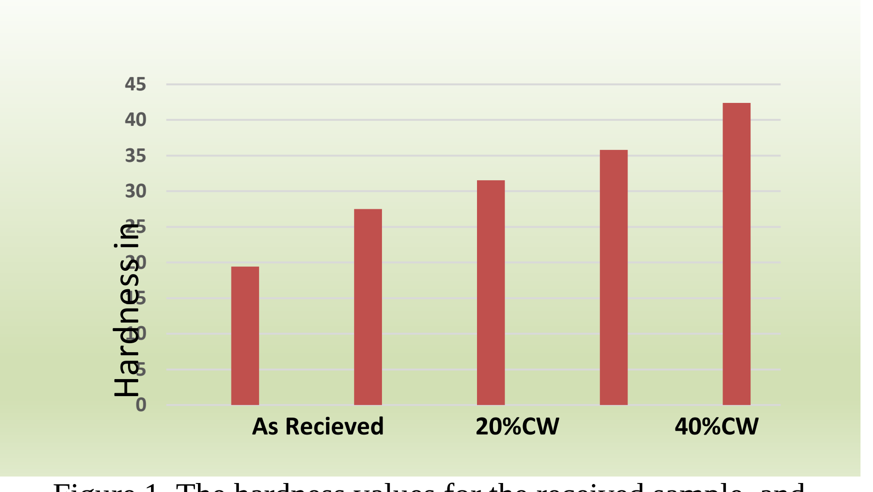

Figure 1. The hardness values for the received sample, and samples with different cold work condition

The average hardness values were 19.4 for the received sample, 27.5 for the 20% cold worked sample, 31.52 for the 40% cold worked sample, 35.8 for the 20% double cold worked sample, and 42.2 for the 40% double cold worked sample respectively. According to the literature, the 316 austenitic stainless steel can only be hardened by the cold working process.
The increasing of the hardness values by increasing the strain hardening is contributing to the formation of the martensite phase along with the austenitic phase in the microstructure of the strain hardened samples. It was observed that the area of martensite phase was increased by increasing the percentage of strain hardening as can shown in figures 2 a,b,c,d. These results are in agreement with other studies[1,6,7] in the literature.

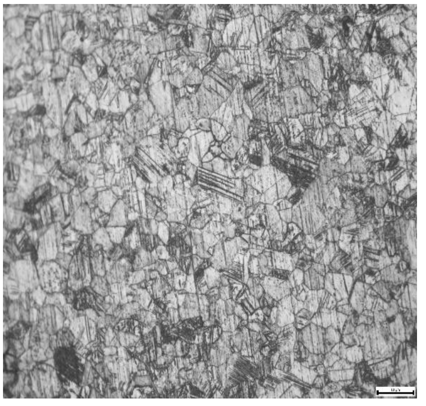

Fig 2a-Microstructure of 20% CW sample (20x)

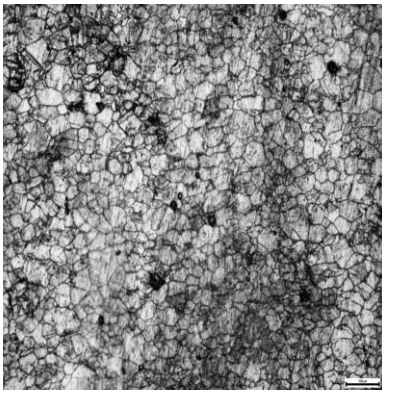

Fig 2b-Microstructure of 40% CW sample (20x)

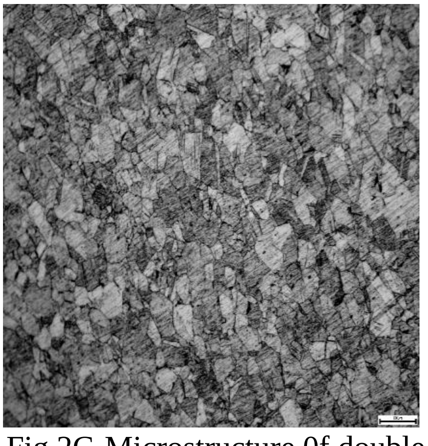

Fig 2C-Microstructure 0f double 20% CW sample (20x)

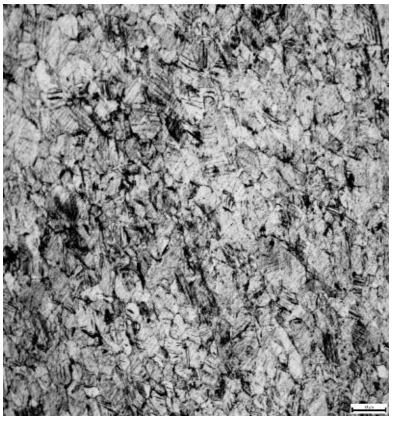

Fig2d- Microstructure of double 40% CW sample (20x)

Table 2 shows the mechanical properties of all samples including the original received sample, 20% CW, 40% CW, pre-strain 20% CW, and pre-strain 40% CW samples. The yield strength increased from 351 N/mm^2 to 407 N/mm^2 when the 316 austenitic stainless-steel samples were subjected to 20% CW and it also increased to 494 N/mm^2 when samples were subjected to 40% CW. When the samples were subjected to the secondary cold working processes, the yield strength values were increased dramatically to 551 N/mm^2

and 785 N/mm^2 for both the pre strained 20% CW and the pre strained 40% samples respectively.
Table 2 also shows that the ultimate tensile strength increased from 653 N/mm^2 for the original received sample to 685 N/mm^2, 718 N/mm^2, 744 N/mm^2 and 851 for the 20% CW, 40% CW, pre-strain 20% CW, pre-strain 40% CW samples, respectively. On the other hand, the elongation percentage was decreased from 94% to 59% when the strain hardening percentage increased.

Table 2. The mechanical properties of 316 stainless steel

Sample type	Yield Strength N/mm^2	Ultimate Tensile Strength N/mm^2	Elongation %
As received	351.00	653.49	94.5
20% CW	407.79	685.08	85.0
40% CW	494.20	718.09	79.0
pre-strain 20% CW	551.11	744.37	79.7
40% CW samples	785.77	851.74	59.7

These results were determined that the 316 Stainless steel becomes harder and stronger after being cold plasticity deformed due to the formation of the martensitic phase.
The increase in both yield and tensile strength is contributed to increase of both martensitic phase and the dislocation density which increased by increasing the strain hardening. This increase in both martensitic phase and dislocation density will cause a restriction in plastic deformation which will increase the strength of the metal. According to eq1 which stated in previos studies (Angelo Fernando Padilha et al[8]),

Conclusions

- The hard and brittle martensite phase increases with the increase of strain hardening ratio.
- After strain hardening of ASS the yield strength and ultimate tensile strength of the sample increase with the increase of strain hardening and martensite phase.

- The elongation decreased with the increase of strain hardening degree, the ductility is measured by elongation, decrease of ductility related to the increase in the ratio of hard and brittle martensite phase.
- The hardness increases with the increase of strain hardening,the hardness value related to the increase in the ratio of hard and brittle martensite phase.

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