Effects of Severe Plastic Deformation on the Mechanical Properties of Welded ST37-2 Steel

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Abstract—**Cold treatment techniques are used to enhance the mechanical properties of metal alloys, whose most important characteristics are strength, roughness, and microstructure. The aim of this research is to test the effect of Conventional Shot Peening (CSP) and Severe Shot Peening (SSP) on the mechanical properties of ST37-2 steel. The results of the experiments showed enhancements in surface roughness and tensile strength. However, shot peening decreased the ductility of the metal and caused changes in its microstructure that are indicated in the XRF and XRD tests. Results' data are provided as an original contribution to the literature while they are compared with the existing data.**

Keywords-ST37-2; shot peening; severe plastic deformation

I. INTRODUCTION

Surface treatment using cold techniques is widely used to enhance the mechanical properties of metal alloys [1]. Shot peening is one of these processes that has an impact on surface roughness, residual stresses, microstructure, and folding of the metal [2]. The effects of plastic deformations resulting from welding or shot peening can be beneficial or have adverse effects on its strength and ductility [3]. Severe plastic deformation (SPD) is formed in metals through processes such as hydrostatic extrusion which deform the metal at low temperatures. SPD results into a fine crystalline structure that differs from the crystallographic structure of the original metal or alloy, through forming micrometric and submicrometric sub-grains in the coarse grain of the original material [4]. The advantages of SPD on the performance and mechanical properties derive from its ability to achieve deformations in the microstructure through fine grains, which reflects on the performance results of hardness and yield stress to saturation levels [5]. The disadvantages of SPD are embodied mainly in the decreased ductility and decreased metal ability to undergo plastic deformation under stress [6].

II. RESEARCH AIM AND METHODS

A. Research Aim

The main aim of the current research is to test the effects of SPD through electric arc welding and shot peening on the mechanical properties and microstructure of ST37-2. It is expected for these processes to affect the microstructure and the homogeneity of the specimens, thus altering their mechanical properties.

B. Material and Sample Preparation

The alloy used in this experiment is ST37-2 (metal content percentages are shown in Table I). The alloy has 0.2% carbon and 0.011% nitrogen maximum content. The tensile strength of the alloy ranges between 360 and 460MPa while it yields at 235MPa with a minimum elongation of 25% [7].

TABLE I. CHEMICAL COMPOSITION OF ST37-2 (%) [8]

Fe	Mn	Si	Al	Cr	Cu	Ni	P	S
98.7012	1.0916	0.0641	0.0408	0.0285	0.0253	0.0235	0.0158	0.0091

After cleaning the steel plates, the samples were initially prepared with dimensions of 400mm length, 200mm width, and 10mm thickness. Plate pairs were welded with an arc welding device with a 10mm welding to form a single plate, as shown in Figure 1. The welding slag was removed with an electric grinding machine. Using a plasma cut, the welded plates were cut into six samples, as shown in Figure 2. Three specimens were prepared for tensile testing and three for fatigue testing. The sample dimensions followed the ASTM specifications of the testing specimens. Figure 3 shows the specimens for tensile and fatigue testing.

Fig. 1. Arc welding of steel plates

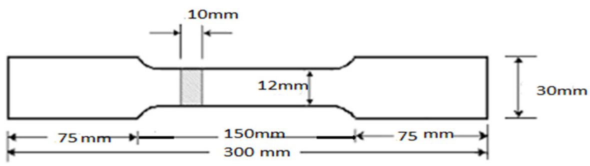

Fig. 2. Testing specimens schematic

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(a)
(b)


Fig. 3. Samples for (a) tensile testing and (b) fatigue testing

Four out of the six specimens were shot peened with two Almen intensities, A12-14 (CSP) and A28-30 (SSP). The shot peening conditions are shown in Table II.

TABLE II. CONDITIONS OF SHOT PEENING FOR CSP (CONVENTIONAL) AND SSP (SEVERE)

Almen intensity	Shot size	Coverage	Duration (sec)	Air pressure (psi)	Arc height (mm)
A12-14 (CSP)	S230	200%	10	30	0.13
A28-30 (SSP)	S230	200%	15	60	0.29

The process of shot peening involves striking the samples with tiny particles with a specific pressure that acts as a hammer on a small area of the surface in order to create indentations or dimples [9]. The process energizes the particles with kinetic energy which is absorbed by the metal surface [10], which then attempts to restore its original condition [11]. The main target of using shot peening is to increase the hardness and fatigue resistance of the samples, while reducing tension [12]. Figures 4-5 show the metal surfaces after using the two types of shot peening. The top picture shows shot peening with A12-14 Almen, while the bottom picture shows shot peening with A28-30 Almen.

Fig. 4. Surface of ST37-2 after shot peening, A12-14

Fig. 5. Surface of ST37-2 after shot peening, A28-30

III. RESULTS AND DISCUSSION

A. Surface Roughness

Three samples were tested for surface roughness: untreated, type A12-14 shot peening, and type A28-30 shot peening. Average roughness (Ra), root mean square roughness (Rq) and average maximum height of roughness profile (Rz) were obtained. Figures 6-8 show the plots of the testing outputs. The results show a significant increase in roughness between the untreated metal and the CSP cases, while more increase in roughness can be observed in the SSP cases. These results are in accordance with the literature. Authors in [13] increased hardness and roughness for engine bladed with shot peening, while authors in [14] showed that the increase in shot peening severity increased surface roughness in ZK60 alloy.

TABLE III. SURFACE ROUGHNESS VALUES

Material	Almen intensity	Ra	Rq	Rz
ST37-2 STEEL	A12-14 (CSP)	6.568	8.174	32.267
ST37-2 STEEL	A28-30 (SSP)	7.466	8.907	34.432
ST37-2 STEEL	As received	0.198	0.253	1.432

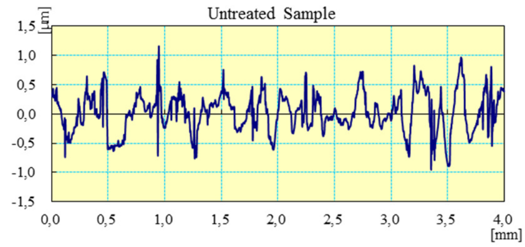

Fig. 6. Roughness test profiles (untreated)

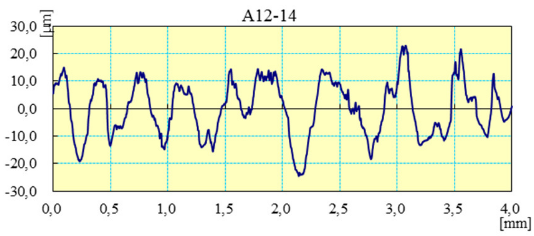

Fig. 7. Roughness test profiles (A12-14)

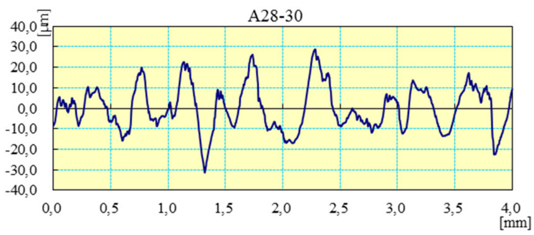

Fig. 8. Roughness test profiles (A28-30)

B. Tensile Test

The force required to break a specimen and its elongation were measured through a tensile strength test according to ASTM D-638, ASTM D-3039, and ASTM C-297 standards. As shown in Table IV, the first sample treated with type A28-30 shot peening retained the yield strength of 360MPa, while the ultimate tensile strength was enhanced by less than 5%. The elongation of the first sample decreased by around 5%. The changes are considered insignificant for the first sample. However, the second sample treated with type A28-30 shot peening showed more significant results as yield strength increased by 19.7%, ultimate tensile strength increased by 22.8%, and elongation decreased by at least 46.8%. The results indicate increased tensile strength accompanied with decreased ductility of the sample. Samples treated with shot peening type A12-14 and those that were not treated with shot peening showed insignificant changes in yield strength and ultimate tensile strength. Figures 9-11 show the plots of the tensile test results. Elongations have decreased at least by 1.2% to 27.2%, confirming the effect of shot peening on the ductility of the alloy. These results are based on standard range values of ST37-2. However, other studies of the alloy showed yield strength and ultimate tensile strength values of 235MPa and 436.8MPa respectively for untreated samples. Therefore, the results of the current study are considered significant in comparison to such results [15]. The results also show that SSP with type A28-30 showed enhanced tensile strength in comparison with CSP which confirms the results of the literature in this aspect [16]. Generally, shot peening showed enhanced strength in comparison with untreated samples [13].

TABLE IV. RESULTS OF TENSILE STRENGTH T TESTING

Material	Almen intensity	YS (MPa)	UTS (MPa)	Elongation (%)
St37-2 steel	A28-30	360	482	23.7
	A28-30	431	565	13.3
	A12-14	352	478	24.7
	A12-14	357	472	20.7
	As received	349	469	18.2
	As received	348	469	23.2

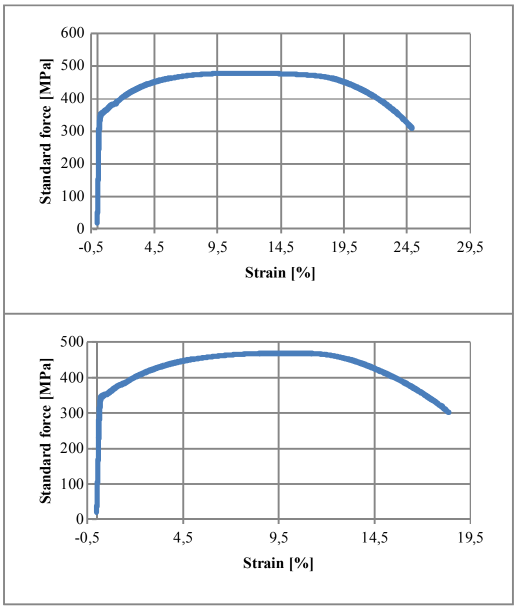

Fig. 9. Tensile test plots for A12-14

C. Microhardness Test

Vickers microhardness test was conducted by applying a load of 1kg for 15s by a ball indicator. Measurements were taken by a calibrated optical microscope for the stress in MPa, as shown in Table V. Shot peening increased microhardness from its original value of 150 for ST37-2 by averagely 21.1% to 47.6% [17]. Authors in [18] showed that microhardness for low carbon steel has an average value of 92, which proves that the obtained hardness values in the current study are a huge enhancement.

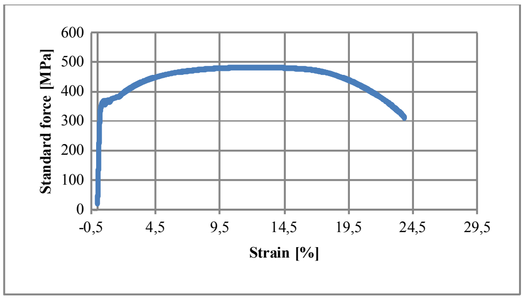

Fig. 10. Tensile test plot for A28-30

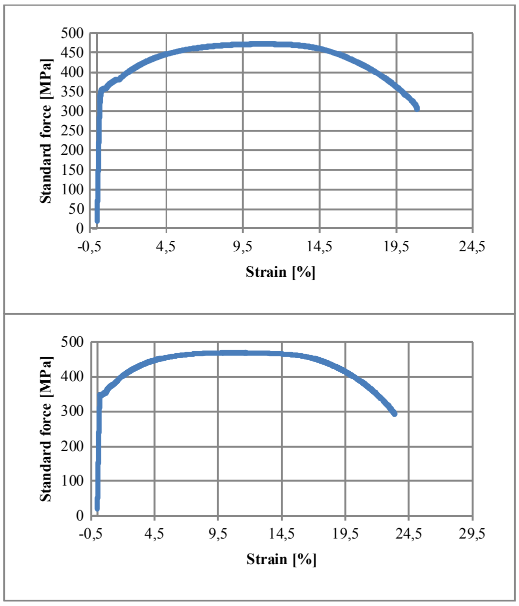

Fig. 11. Tensile plots for the untreated samples

TABLE V. VICKERS MICROHARDNESS TEST VALUES

Almen intensity	Value (1)	Value (2)	Value (3)	Average
A28-30	222	224	218	221.33
A12-14	189	192	188	189.67
As received	183	181	181	181.67

D. XRF Analysis

X-Ray Fluorescence (XRF) is a microscopy method that is used to measure the concentration of metals in a specific area. The method depends on the interaction between the x-ray arrays with the matter by dislodging electrons from atoms, measuring the resulting energy and correlating it with a specific element [19]. As seen from the results of the XRF (Table VI), the mass percentage of each metal component has been changed through shot peening, while the analysis depth ranged between 0.0009 and 0.0355mm.

TABLE VI. XRF ANALYSIS OF ST37-2

Component	Result	Unit	EI line	Det. Limit	Intensity	w/o normal	Analyzing depth (mm)
Al	0.0408	Mass%	0.00204	Al-KA	0.3807	0.0418	0.0009
Si	0.0641	Mass%	0.00205	Si-KA	0.6215	0.0656	0.0013
P	0.0158	Mass%	0.00103	P-KA	0.4290	0.0161	0.0018
S	0.0091	Mass%	0.00072	S-KA	0.2240	0.0093	0.0025
Cr	0.0285	Mass%	000432	Cr-KA	0.6336	0.0292	0.0230
Mn	1.0916	Mass%	0.00870	Mn-KA	20.4876	1.1177	0.0265
Fe	98.7012	Mass%	0.02378	Fe-KA	2319.6146	101.0629	0.0355
Ni	0.0235	Mass%	0.00802	Ni-KA	0.2879	0.0241	0.0066
Cu	0.0253	Mass%	0.00556	Cu-KA	0.3890	0.0259	0.0104

E. XRD Analysis

In order to identify crystalline material in the samples that were treated with shot peening, X-Ray powder Diffraction (XRD) analysis was used. Figure 12 shows the peaks of three samples, which are identical in phase pattern and position, while differing in intensity. The matching patterns and positions are signs of error absence in positioning during the experiment. The slightly higher broadening at 64.85 and 82.27 degrees indicates minor nanocrystalline ceria. The three peaks shown in the figure show that changes in the micro-strains have occurred with shot peening and their intensities decreased with the increase of the severity of the deformation through shot peening in the metal.

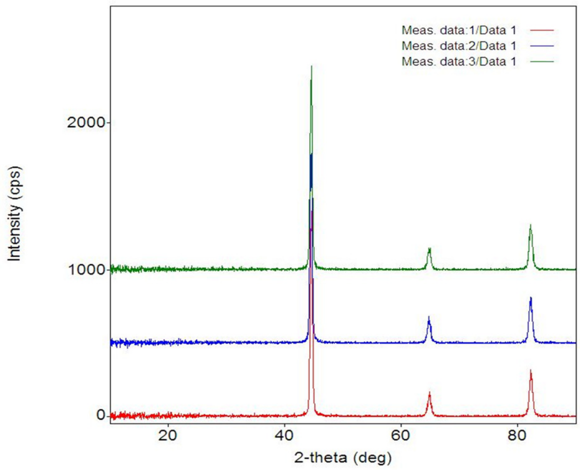

Fig. 12. Diffractogram of XRD analysis

F. Optical Microscope

Two specimens were investigated with an optical microscope (Figure 13) to study the microstructure and mechanical changes of the shot peening treatment. Shot peening with CSP A12-14 Almen intensity affected a thin layer with minimum influence, while shot peening with SSP A28-30 Almen intensity had a higher intensive influence to a thicker layer. In the SSP case, an intrinsic structure is observed. The ferrite and perlite phases are clear with SSP A28-30 [20].

G. Scanning Electron Microscopy (SEM)

As shown in Figure 14, the specimens treated with shot peening were tested with SEM. Both A12-18 and A28-30 Almen intensities yielded plastic deformations. Disturbances were increased in the SSP case, while it created more intense bumps and pits. Layer thickness was increased by 24.4% in the SSP case in comparison with the CSP case. The homogeneity of the alloy did not seem to be affected in both samples by shot peening, however the increase in hardness as confirmed by the hardness test is reflected by the formation of connected deformed structures [21].

(a)

(b)

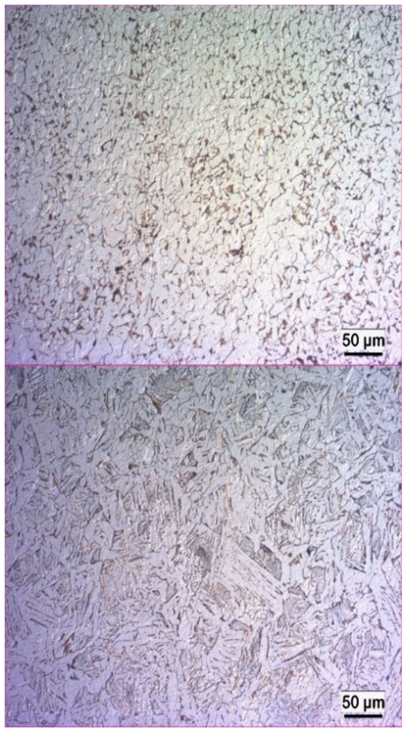

Fig. 13. Optical microscope images for shot peened samples: (a) CSP A12-14, (b) SSP A28-30 (bottom)

(a)

(b)

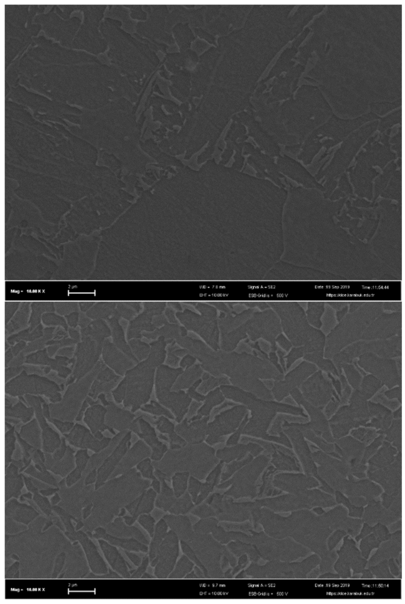

Fig. 14. FESEM images of plastic deformed layer of shot peened specimens: (a) CSP A12-14 (top-layer thickness=7.8μm), (b) SSP A28-30 (bottom-layer thickness=9.7μm)

IV. CONCLUSION

The enhancement of alloy properties can be achieved through cold techniques such as shot peening, targeting improvements in strength, roughness, and microstructure. The current research aims to investigate the effects of conventional (CSP) and severe (SSP) shot peening on the mechanical properties of ST37-2 steel through their comparison with untreated specimens, and performing an arc weld as severe plastic deformation (SPD). Two Almen intensities were used, A12-14 and A28-30. The surface roughness values showed substantial increases in Ra, Rq and Rz values between A12-14 and untreated ST37-2 samples, while a higher increase in roughness was achieved with A-23-30 shot peening. The tensile strength results show enhancements in yield strength and ultimate tensile strength values reaching up to 19.7% and 22.8% with SSP, while elongation decreased up to 27.2% confirming the decrease in ductility with shot peening. The hardness of the alloy increased in treated samples and the changes in microstructure were exhibited by XRF and XRD analyses. Deformation intensities were investigated with optical microscopy and were found to have increased while a layer thickness increase in the SSP case (in comparison with the CSP case) was observed. Some data confirm the past literature findings, while the research contributes to the relevant literature with original data.

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