The effect of surface mechanical attrition treatment (SMAT) on plastic deformation mechanisms and mechanical properties of austenitic stainless steel 316L

Elham Rajabi, Reza Miresmaeili and Mahmood Aliofkhazraei

Department of Materials Engineering, Tarbiat Modares University, Tehran, Iran

1 Postal address: Department of Materials Engineering, Tarbiat Modares University, Jalal Ale Ahmad Highway, PO Box: 14115-143, Tehran, Iran.

E-mail: miresmaeili@modares.ac.ir

Keywords: surface mechanical attrition treatment, austenitic stainless steel, mechanical properties, plastic deformation mechanisms

Abstract

In this work, surface mechanical attrition treatment (SMAT) was carried out on 316L stainless steel in order to study the effects of treatment parameters on the deformed depth and deformation mechanisms. Results showed that the residual stresses caused by collision of shots led to formation of martensite. Increase in treatment duration and shot size led to more martensite formation because of higher strains. An increasing hardness profile was also observed from the depth towards the surface in SMATed samples which was due to grain refinement, martensite formation and twinning. Strength of samples also was improved by SMAT so that the yield strength in the sample treated for 2 h by 6 mm shots was increased by 58 percent. In addition, Crussard-Jaoul diagrams for samples treated under various conditions and untreated samples were compared. It was observed that slope variation occurred earlier in SMATed samples. In other words, mechanisms were activated at lower strains.

1. Introduction

Surface is one of the most important parts of industrial devices due to majority of failures in engineering material initiates on the surface; hence, there are many surface treatment procedures to improve surface properties of metals [1]. Once a metal is plastically deformed at intermediate temperatures, the internal structure of the metal begins to resist against further deformation. This phenomenon is called work hardening. In fact, work hardening increases strength and hardness of metal by deformation [2, 3]. A well-known method in the field of severe plastic deformation is surface mechanical attrition (SMAT) which was developed in recent years in order to improve surface properties of materials [4]. This method includes spherical shots made of steel or a ceramic under vibration in a container. Shots are excited by a generator and impact the surface of sample at 1–20 m.s\(^{-1}\) applying high strains that lead to grain refinement and improvement of mechanical properties over the surface [2, 3]. A grain size profile, from nanometers (on top) to micrometers (core), forms in the sample in accordance with the variations in strain profile and strain rate from the treated surface towards the core [6].

Plastic deformation behavior and dislocations movement in metals is strongly dependent on the lattice structure and stacking fault energy (SFE). Strain accumulation occurs in materials with high SFE values due to formation of dislocation cells and walls; therefore, coarse grains are divided to smaller parts [7]. However, deformation mechanism in low SFE materials may change from slip to mechanical twinning especially under high strain rates or at low temperatures [8]. Xu et al.[9] reported in their study on stainless steel that stacking fault energy in austenitic stainless 316LN was 18.9 mJ.m\(^{-2}\). They also stated that deformation mechanism would be mechanical twinning, martensite formation due to strain application or a combination of both if SFE values were within 15 to 20 mJ.m\(^{-2}\).

Austenitic stainless steel features appropriate corrosion resistance while it has relatively poor strength properties and yield strength of coarse-grained samples is 350–450 MPa. Therefore, the microstructure is...
in SMATed samples, which consisted of coarse- and austenitic stainless steel. Considering previous studies merely included plastic deformation mechanism of twinning stainless steel under tensile forces are dislocations slip, formation of martensite due to residual stresses and

\[ \text{size of the deformation zone depends on SMAT parameters including shot diameter, frequency and duration} \]

Dominant deformation mechanisms in stainless steel under tensile forces are dislocations slip, formation of martensite due to residual stresses and twinning. The main goal of the present work is to investigate the effect of SMAT on strengthening mechanisms in austenitic stainless steel. Considering previous studies merely included plastic deformation mechanism of coarse- and fine-grained samples under tensile forces, we decided to investigate plastic deformation mechanism in SMATed samples, which consisted of fine-grained surfaces and coarse-grained bulks.

### 2. Materials and methods

An austenitic stainless steel sheets with thickness of 3 mm and grain size of 35 μm were used in the present work. The sheet was cut to pieces of 28 × 50 mm. High carbon steel shots of 3 and 6 mm in diameter were selected. The treatment process was conducted for 1 and 2 h. Samples were washed with water and soap and device container was cleaned by a cloth prior to each shot-peening step. In order to prevent contamination of samples surfaces, peening shots were replaced after several steps depending on the sample type and process duration. New samples were washed before usage by water, soap and acetone. In each step, the shots covered almost 75 percent of the container floor. Total weights of 3 mm and 6 mm shots were 50 and 102 g, respectively. Chemical analysis of the steel sheet is presented in table 1.

The SMAT machine used in the present work had a mechanical generator that converted electrical energy to mechanical energy using an electrical engine. It is a custom-built motor-driven type of SMAT. The driving force is supplied through an AC electric motor. machine frequency varied between 5 to 7 Hz. Unlike other machines in which shots impact the samples at various directions, shots impacted at approximately 90° to the sample in this machine. Machine container is a stainless steel hollow cylinder which is 80 mm in diameter and 90 mm in height. Shots are placed inside the cylinder and two samples are fixed on the container caps. Up and down movement of the chamber causes shots to impact the samples surface in approximately 90° manner.

The treatment process was in steps because we had to reverse (turn over) samples to avoid bending and increasing temperature due to impact of shots. SMATed samples were cross-sectioned, mounted and polished in order to investigate their microstructure through optical and electron microscopies at various magnifications. SiC sandpapers with grit sizes of 60 to 3000 were used for grinding. Then, samples were polished using an alumina solution containing 0.3 μm particles. The austenitic stainless steel samples were etched using glycergia solution containing HCl (15 ml), HNO₃ (10 ml) and acetic acid (10 ml). OLYMPUS BX51M optical and Philips XL30 electron microscopes were employed. Kaling’s No.1 reagent containing ethanol (33 ml), distilled water (33 ml), hydrochloric acid (33 ml) and CuCl₂ (1.5 g) was used for martensite detection. Microhardness of samples was measured using a 50 g load according to the Vickers method for 15 s by a Bohler microtest device. The average values of indented diameters and their distance from the surface was measured on an optical micrograph provided at 500X using Olympus software. In addition, some of the samples, after being washed with water and soap, were tested by a 500 g load for 15 s.

Both sides of samples were SMATed for the tensile test. Tensile test samples were produced after SMAT by electrical discharge machining in accordance with ASTM E8 standard code. Samples were subjected to the tensile testing using a SANTAM test device. Each test was repeated three times in order to assure the repeatability of findings.

Approximate grain size of samples was calculated by XRD analysis using a Philips X’Pert MPD diffractometer with cobalt Kα radiation. The 2θ scanning range was from 10° to 120° with a scanning step of 0.02degree.s⁻¹. The applied SMAT parameters and samples are given in table 2.

### Table 1. Chemical composition of austenitic stainless steel.

| Element | C     | Si    | Mn    | P     | S     | Cr    | Mo    | Ni    | Co    |
|---------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Base    | 0.027 | 0.41  | 1.06  | 0.051 | 0.005 | 17.17 | 2.31  | 10.15 | 0.27  |
| Cu      |       |       |       |       |       |       |       |       |       |
| Nb      |       |       |       |       |       |       |       |       |       |
| Ti      |       |       |       |       |       |       |       |       |       |
| V       |       |       |       |       |       |       |       |       |       |
| W       |       |       |       |       |       |       |       |       |       |
| Sn      |       |       |       |       |       |       |       |       |       |
| Ca      |       |       |       |       |       |       |       |       |       |
| B       |       |       |       |       |       |       |       |       |       |
| N       |       |       |       |       |       |       |       |       |       |

Approximate grain size of samples was calculated by XRD analysis using a Philips X’Pert MPD diffractometer with cobalt Kα radiation. The 2θ scanning range was from 10° to 120° with a scanning step of 0.02degree.s⁻¹. The applied SMAT parameters and samples are given in table 2.
3. Results

3.1. Microstructure analysis

SEM micrographs of austenitic stainless steel cross sections, before and after treatment, are shown in figure 1. Figure 1(b) shows that SMAT lead to formations of twins near the vickerle. Figure 1(c) which is the magnified square shown in figure 1(b) exhibits the twin-martensite intersection. In fact, strain induced austenite conversion to martensite.

Figure 2 shows the micrographs of cross sections of samples SMATed for various times and using different ball diameters. The deformed depth that indicates twins and twin-martensite intersections is defined by a red line. The corresponding values are presented in table 3. According to table 3 that gives depth of deformed areas in different samples, the depth values increased with increase in time and shot diameter. The increase in depth over SMAT time was more significant for 6 mm shots than 3 mm ones. It may be observed that the highest and lowest depth values were for 2h-6mm and 1h-3mm samples, respectively.

In order to measure the martensite depth, Kalling’s No.1 etchant which darkens the martensite regions was used. Depth of martensite increased with increase in time and shot diameter (see figure 3). The sample SMATed for 2 h by 6 mm shots had the highest martensite depth; while, the sample SMATed for 1 h by 3 mm shots showed the lowest martensite depth. It appears that, due to its higher formation energy, less martensite was

| Samples | Time (h) | Shot diameter (mm) |
|---------|----------|-------------------|
| reference | 0 | — |
| 1h-3mm | 1 | 3 |
| 2h-3mm | 2 | 3 |
| 1h-6mm | 1 | 6 |
| 2h-6mm | 2 | 6 |

Figure 1. SEM micrographs of sample cross section: (a) before treatment at low magnification, (b) after treatment at low magnification and (c) the magnified image of square shown in b.
formed in comparison with the deformed area. The martensite appeared outside the deformed layer area was probably caused by application of extreme forces during sample preparation (grinding and polishing) [17].

XRD analysis was performed on all SMATed samples in order to investigate the martensite as well as to calculate the grain size. Figure 4 shows that the intensity of peaks regarding martensite invariably increased after SMAT.

3.2. Microhardness
Surface mechanical attrition treatment was conducted on 316L austenitic stainless steel samples for 1 and 2 h using 3 mm and 6 mm shots. Microhardness of raw and treated samples was tested in terms of the distance from the surface. It was observed that hardness of SMATed samples gradually decreased from the surface towards the core where it equaled hardness of the base metal. In addition, hardness of samples treated with 6 mm shots was greater than those treated with 3 mm shots. Hardness increased with increase in treatment time (see figure 5).

Hardness versus distance plots may be used for calculation of depth of the deformed layer. It may be observed in figure 2 that the hardening depth, which indicates the depth of the deformed layer, was 450 and 500 μm in samples treated for 2 h by 3 and 6 mm shots, respectively. Depth of the hardened layer increased with increase in time and shot diameter. The highest hardening depth (i.e. the deformed layer depth) was attributed to the 2h-6mm sample. Figure 6 may be used to gather a better comparison between hardening depth values of samples. It also shows that hardening depth increased with increase in treatment time and shot diameter.

3.3. Tensile test
1 mm thickness sample was used for SMAT process to prepare tensile specimens so that we can see the effect of SMAT on tensile properties more clearly with decreasing the ratio of deformed layer to the thickness of sample.

Table 3. Depth of the deformed areas in various samples.

| Sample     | 2h-6mm | 1h-6mm | 2h-3mm | 1h-3mm |
|------------|--------|--------|--------|--------|
| depth (μm) | 200    | 101    | 70     | 52     |

Figure 2. SEM micrographs of cross sections of (a) 2h-6mm, (b) 1h-6mm, (c) 2h-3mm and (d) 1h-3mm.
After being SMATed on both sides, samples with thickness of 1 mm along with a raw sample were subjected to tensile test under an engineering strain rate of 0.005 s\(^{-1}\). Figure 7 shows that tensile properties of samples SMATed by 6 mm shots for 1 and 2 h are superior to those treated by 3 mm shots. For the same time Surface mechanical attrition treatment on both sides led to grain refinement and martensite formation. Consequently, hardness and yield strength of samples increased. It may be observed in table 4 that samples SMATed with 6 mm shots showed a higher strength than those treated via 3 mm shots. For the same time In addition, increase in SMAT duration led to improvement of samples strength. In fact, depth of the deformed layer was increased by increase in shot diameter leading to improvement of samples strength.
4. Discussion

4.1. Changes in microstructure and mechanical properties of austenitic stainless steel after SMAT

Strain induced by SMAT causes severe plastic deformation on the surface. In result, severe plastic deformation leads to grain refinement by several mechanisms including creation, accumulation and intersection of defects such as dislocations, twins and low angle grain boundaries. Grain refinement over the surface increases hardness. It may be observed in figure 1 that there was no twinning in samples before treatment. However, twins and their intersection with martensite were seen after treatment processes. Grain size refinement takes place in a
Figure 6. Clustered column plot of the hardening depth.

Figure 7. Engineering stress–strain curves of samples SMATed for (a) 1 h and (b) 2 h.

Table 4. Variations in tensile properties under various conditions.

| Sample     | UTS (MPa)  | Yield Strength (MPa) | Elongation (%) |
|------------|------------|----------------------|----------------|
| Reference  | 778.7 ± 14.4 | 484.4 ± 20.2         | 58.71 ± 0.14   |
| 1h-3mm     | 807.9 ± 2   | 639.7 ± 8.7          | 46.5 ± 0.16    |
| 2h-3mm     | 856.3 ± 8.7 | 688.7 ± 2.9          | 48.25 ± 0.25   |
| 1h-6mm     | 868.3 ± 3.3 | 725.5 ± 26           | 46.08 ± 0.004  |
| 2h-6mm     | 891 ± 17.3  | 764.3 ± 5.7          | 40.88 ± 0.31   |
The steel shots applied very high strains onto the surface leading to formation of nano-scale grains. Martensite content in different samples was calculated by equation (1) [18]. The calculated martensite contents using XRD data are given in table 6. It may be observed that martensite content increased over time. Increase in shot size from 3 to 6 mm, during one hour of treatment, led to increase in martensite content. However, martensite content in the 2h-3mm sample was slightly higher than the 2h-6mm sample. This may be due to saturation of martensite formation. According to figures 2 and 3, the larger shot led to formation of a deeper deformed layer and more martensite in comparison with the smaller shot. Since XRD is a surface analysis, it is possible that one hour is the required time for saturation of martensite in depth of the surface. In fact, formation of martensite and twins led to reduction of dislocations slip and improvement of surface hardness. Dislocations percentage increases with increase in the applied strain; hence, dislocations movement is barricaded leading to activation of twinning mechanism. In addition, austenite content was seen to decrease while martensite content increased. Presence of martensite over the SMATed surface was confirmed by Kalling’s etchant (figure 3) and XRD patterns (figure 4). Martensite α’ nuclei formed by strain are located in shear bands, micro-bands, twins, stacking faults in planes and martensite ε which, in turn, is induced by severe plastic deformation. Increase in the cold work leads to formation of more defects within the microstructure so that there would be more proper sites for nucleation of α’ martensite. Therefore, intersection of martensite with twins occurred near the SMATed surface due to the high levels of applied strain. In other words, the required strain for martensite formation was high so that martensite formed near the surface. This is shown by the martensite depth in figure 3. The martensite depth (figure 3) was smaller than the hardened layer thickness (figure 5) which is due to lower strain-induced martensite transformation. Hence, increase in depth of hardness was due to plastic deformation, twinning and work hardening. In fact, twinning occurred within a higher depth than martensite formation. In a study on 304 austenitic stainless steel samples, Thangaraj et al. [11] reported intersection of martensite with twins over the SMATed surface. Grain size values of 2h-6mm and 2h-3mm samples were 19.2 and 27.6 nm, respectively, which might be due to the fact that work hardening saturation occurs between 1 and 2 h of treatment. (see figure 5(b)).

Figure 1(c) illustrates an intersection between twins and martensite as shots caused formation of the latter by application of strains on the surface. Dislocations percentage increases with increase in the applied strain; hence, dislocations movement is barricaded leading to activation of twinning mechanism. In addition, austenite content was seen to decrease while martensite content increased. Presence of martensite over the SMATed surface was confirmed by Kalling’s etchant (figure 3) and XRD patterns (figure 4). Martensite α’ nuclei formed by strain are located in shear bands, micro-bands, twins, stacking faults in planes and martensite ε which, in turn, is induced by severe plastic deformation. Increase in the cold work leads to formation of more defects within the microstructure so that there would be more proper sites for nucleation of α’ martensite. Therefore, intersection of martensite with twins occurred near the SMATed surface due to the high levels of applied strain. In other words, the required strain for martensite formation was high so that martensite formed near the surface. This is shown by the martensite depth in figure 3. The martensite depth (figure 3) was smaller than the hardened layer thickness (figure 5) which is due to lower strain-induced martensite transformation. Hence, increase in depth of hardness was due to plastic deformation, twinning and work hardening. In fact, twinning occurred within a higher depth than martensite formation. In a study on 304 austenitic stainless steel samples, Thangaraj et al. [11] reported intersection of martensite with twins over the SMATed surface. Grain size values of 2h-6mm and 2h-3mm samples were 19.2 and 27.6 nm, respectively, which were calculated using Williamson-Hall equation. The steel shots applied very high strains onto the surface leading to formation of nano-scale grains. Martensite content in different samples was calculated by equation (1) [18].

\[
\frac{\sum_{i=1}^{n} V_i}{\sum_{i=1}^{n} \frac{I_i}{R_i}} = \frac{\sum_{i=1}^{n} \frac{I_i}{R_i}}{V_t}
\]

Where \(V_t\) is volume of a given phase, \(I_i\) is intensity of a given phase, \(n\) is the number of existing phases and \(R_i\) is intensity factor which its values are presented in table 5.
Therefore, martensite content in the 2h-3mm surface was slightly higher than that of 2h-6mm while martensite depth in the 2h-6mm sample was larger than the 2h-3mm sample.

Martensite percentage in cross sections was calculated using MIP software from the samples etched by Kalling’s reagent (table 7). It may be observed that martensite percentages for 1h-3mm and 2h-3mm samples were close values which may be due to saturation of martensite after treating for an hour using 3 mm shots. However, martensite percentage increased over time once 6 mm shots were used. Generally, increase in shot diameter led to increase in martensite percentage over 1 h and 2 h treatment durations.

According to table 4, increase in shot diameter and treatment time improved tensile and yield strengths. Although elongation of the sample SMATed by 3 mm shots for 1 h was less than that treated for 2 h, this slight difference may be attributed to the device error. Both tensile and yield strengths considerably increased over time. Note that time increase effect on improvement of yield strength was bolder from 0 to 1 h in comparison with 1 to 2 h. This indicates reaching the work hardening saturation point. Surface mechanical attrition treatment improved yield strength of 2h-3mm and 2h-6mm samples by 43% and 58%, respectively.

Figure 8 illustrated true strain–stress curves of different samples. True stress ($\sigma$) is load divided by instant cross section, F/instant cross section and true strain ($\varepsilon$) is Ln($l_2/l_1$). Engineering stress is F/initial cross section and engineering strain is ($l_2-l_1)/l_1$. All SMATed samples show improvement of strength. The work hardening

| 2h-6mm | 2h-3mm | 1h-6mm | 2h-6mm |
|--------|--------|--------|--------|
| 20.48% | 14.59% | 13.59% | 13.28% |

Figure 8. True stress–strain diagrams for various samples: (a) 6 mm shots, (b) 3 mm shots.
behavior of 2h-6mm sample is compared with that of the untreated sample in figure 9. The continuous line represents the true stress-strain curve and the dashed line is the n (work hardening exponent) curve. n is obtained by equation (2).

\[ \sigma = K\varepsilon^n \] (2)

It may be observed that strength of the SMATed sample was higher than the untreated one while its work hardening exponent is smaller. In fact, work hardening, grain refinement and martensite formation by SMAT led to improvement of sample strength. Thus, deformation ability of the SMATed sample i.e. work hardening exponent reduced.

Crussard-Jaoul (C-J) diagrams (where ordinate is \( \ln(d\sigma/d\varepsilon) \) and abscissa is \( \ln(\varepsilon) \)) were plotted to study the deformation mechanism for various samples in figures 10 and 11. Figure 10(a) shows the C-J curve for the reference sample. Figures 10(b), (c), 11(a) and (b) illustrate C-J curves for samples SMATed by 6 mm and 3 mm shots. These curves consist of several steps based on slope variation which are shown for each sample. Slope variation indicates activation of deformation mechanism under tensile tests. Deformation mechanism depends on the stacking fault energy. Martensite formed in 316 austenitic stainless steel samples due to presence of strains during deformation. In addition, activation of mechanical twins in these steel samples was reported in many studies on super-refined austenitic stainless steel samples [9]. Chala et al [10] investigated the tensile behavior of coarse-grained and super-refined austenitic stainless steel samples and compared their deformation mechanisms. Martensite formed in the coarse-grained austenitic stainless steel due to the applied strains while the observed mechanism in the super-refined austenitic stainless steel was formation of nano-twins since austenite stability increases with reduction of grain size. There have been many studies on austenitic stainless steel that showed formation of twins during the tensile test [9, 10, 17, 19, 20].

The C-J diagram of the coarse-grained austenitic stainless steel (reference sample) includes 5 steps (A-E) as shown in figure 10(a). The curve slope generally reduced in step A caused by the easy slip of dislocations. Increase in the slope in step A indicates dislocations pile-up that, in turn, increases the work hardening rate. In addition, shear bands may form for facilitating movement of dislocations; hence, work hardening rate reduces and slope of the curve would decrease. Formation of shear bands shows a double behavior in work hardening rate. In fact, formation of shear bands facilitates dislocations movement; yet, on the other hand, these bands may restrict movement of dislocations and consequently increase the work hardening rate. It can be deduced, therefore, the step A itself may have several parts. This is why actually increase and decrease in slope was observed in step A (parts I, II and III). Step A in the reference sample began from the 0.05. The same step in the 2h-6mm sample started from 0.066. Chala [20] and Xu [9] also reported that step A started earlier in the coarse-grained samples due to the delay in yield (i.e. improvement of yield strength) caused by surface mechanical attrition treatment. Increase in the work hardening rate was observed in step B which may be due to formation of twins and nano-twins. Twins act as barriers against dislocations movement and thus increase the work hardening rate [20, 21]. The increase in the untreated samples (figure 10(a)) was very small compared with the SMATed ones (figures 10(b) and (c)). Formation of twins and nano-twins was observed elsewhere in austenitic stainless steel microstructure to occur at 0.1 [9, 10]. Slope increase in step B for the reference sample started at 0.2. Therefore, this slope variation may be attributed to twinning. Slope decreased in step C. Nucleation and growth of twins
probably ended in this step and saturation occurred. Twins tend to form cells which cause reduction of the work hardening rate [22]. Previous studies on 316 austenitic stainless steel samples revealed formation of nano-twins during the tensile test [19]. The next step is D which shows increase in the slope and may be attributed to nucleation of martensite. Twins intersection may be a suitable site for martensite nucleation [12 and 23]. In fact, martensite is caused by strain application acting as a barrier against dislocations movement so that work hardening rate would increase. Chung [24] studied TRIP steels and observed that formation of martensite led to increase in the work hardening rate. The final step is E in which martensite grows and thickens while their nucleation rate is diminished. Consequently, movement of dislocations is facilitated. The slope plummeted in this step due to necking [10 and 20].

Figures 10(b), (c), 11(a) and (b) illustrate C-J diagrams for 1h-6mm, 2h-6mm, 1h-3mm and 2h-3mm samples, respectively. Similar to the reference sample, these curves include five steps. It may be pointed out that SMAT changed steps lengths and slopes. Twins percentage and martensite content increased with increase in treatment time due to increase in the applied energy over the surface and consequently increase in thickness of the work hardened region. In result, the five steps are distinguished better in samples SMATed for 2 h instead of 1 h or untreated samples. Slope variation occurred earlier in SMATed samples (figures 10(b) and (c)) than in the reference sample (figure 10(a)). In other words, twinning and martensite formation activated in lower strains whereas the difference for 1h-3mm and 2h-3mm samples was insignificant.
5. Conclusion

Austenitic stainless steel samples were subjected to SMAT by 3 and 6 mm shots for 1 and 2 h. After hardness and tensile measurements, the following conclusions were obtained:

- SMAT led to formation of twins by application of strain over the surface. It also increased dislocations percentage, created minor boundaries and led to grain refinement. Surface hardness and strength improved by SMAT through work hardening and increasing the thickness of the deformed layer.

- Increase in the shot diameter led to application of more strain over the surface and increase in thickness of the deformed layer which, in turn, improved strength of the treated samples.

- SMAT led to conversion of austenite to martensite by application of compressive stress over the surface of austenitic stainless steel samples. It formed super-refined grains (nano-scale) and improved surface hardness.

- The larger the shots, the more strain was applied over the surface leading to increase in depth of the deformed region and martensite.

- Martensite formation reached saturation after 1 h of treatment by 3 mm shots. However, martensite depth increased in the sample treated by 6 mm shots by increase in treatment time from 1 h to 2 h.

- Martensite-twins intersections were observed in SEM micrographs. Kalling’s etchant proved presence of martensite in all SMATed samples. It was shown that martensite content increased with increase in treatment time and shot diameter.

- Hardness and tensile tests revealed that the deformed region was escalated by increase in shot diameter due to application of larger strains. Hence, hardness and strength improved.

- Deformation mechanisms in samples were determined by C-J diagrams before and after treatment. These mechanisms included slip, twinning and martensite formation. SMAT emboldened slope variations during twins and martensite formation processes. It also accelerated the mechanisms activation processes.
ORCID iDs
Reza Miresmaeili  https://orcid.org/0000-0002-2567-9094

References
[1] Bagheri S and Guagliano M 2009 Review of shot peening processes to obtain nanocrystalline surfaces in metal alloys Surf. Eng. 25 3–14
[2] Hosford W F and Caddell R M 2011 Metal Forming: Mechanics and Metallurgy (Cambridge: Cambridge University Press)
[3] Stolyarov Y V, Zhiu Y T, Lowe T C, Islamgaliev R K and Valiev R Z 1999 A two step SPD processing of ultrafine-grained titanium Nanostruct. Mater. 11 947–54
[4] Wang Z B, Tao N R, Li S S, Wang W, Liu G, Lu J and Lu K 2003 Effect of surface nanocrystallization on friction and wear properties in low carbon steel Materials Science and Engineering: A 352 144–9
[5] Valiev R Z, Islamgaliev R K and Alexandrov I V 2000 Bulk nanostructured materials from severe plastic deformation Prog. Mater. Sci. 45 103–89
[6] Groza J R and Shackelford J F 2007 Materials Processing Handbook (Boca Raton, FL: CRC Press)
[7] Azadmanjiri I, Berndt C C, Kapoor A and Wen C 2013 Development of surface nano-crystallization in alloys by surface mechanical attrition treatment (SMAT) Crit. Rev. Solid State Mater. Sci. 40 164–81
[8] Zhang H W, Hei Z K, Liu G, Lu J and Lu K 2003 Formation of nanostructured surface layer on AISI 304 stainless steel by means of surface mechanical attrition treatment Acta Mater. 51 1871–81
[9] Xu D M, Li G G, Wan X L, Xiong R L, Xu G, Wu K M, Somani M C and Misra R D 2017 Deformation behavior of high yield strength–High ductility ultrafine-grained 316LN austenitic stainless steel Materials Science and Engineering: A 688 407–15
[10] Challa V S, Wan X L, Somani M C, Karjalainen L P and Misra R D 2014 Strain hardening behavior of phase-reversion-induced nanograined/ultrafine-grained (NG/UF) austenitic stainless steel and relationship with grain size and deformation mechanism Materials Science and Engineering: A 613 60–70
[11] Thangaraj R, TN Nellaiappan SN, Kulandaivelu R, Lee M H and Nishimura T 2015 A facile method to modify the characteristics and corrosion behavior of 304 stainless steel by surface nanostructuring toward biomedical applications ACS Applied Materials & Interfaces 7 17731–47
[12] Lehnhoff G R and Findley K O 2014 The martensitic transformation and strain-hardening behavior of austenitic steels during fatigue and tensile loading JOM 66 756–64
[13] Misra R D, Challa V S, Venkatasurya P K, Shen Y F, Somani M C and Karjalainen L P 2015 Interplay between grain structure, deformation mechanisms and austenite stability in phase-reversion-induced nanograined/ultrafine-grained austenitic ferrous alloy Acta Mater. 84 339–48
[14] Astarazee A H, Miresmaeili R, Bagherifard S, Guagliano M and Aloiokhazraei M 2017 Incorporating the principles of shot peening for a better understanding of surface mechanical attrition treatment (SMAT) by simulations and experiments Mater. Des. 116 365–73
[15] Rajabi M, Miresmaeili R and Aloiokhazraei M 2019 Hardness and wear behavior of surface mechanical attrition treated titanium Materials Research Express 6 065003
[16] Changgordani S A, Miresmaeili R and Aloiokhazraei M 2018 Improvement in tribological behavior of commercial pure titanium (CP-Ti) by surface mechanical attrition treatment (SMAT) Tribol. Int. 119 744–52
[17] Yan F K, Tao N R, Arche F, Gutierrez-Urrutia I, Raabe D and Lu K 2014 Deformation mechanisms in an austenitic single-phase duplex microstructured steel with nanotwinned grains Acta Mater. 81 487–500
[18] Yang Q and Luo J L 2000 Martensite transformation and surface cracking of hydrogen charged and outgassed type 304 stainless steel Materials Science and Engineering: A 288 75–83
[19] Liu G Z, Tao N R and Lu K 2010 316L austenite stainless steels strengthened by means of nano-scale twins Journal of Materials Science & Technology 26 289–92
[20] Challa V S, Wan X L, Somani M C, Karjalainen L P and Misra R D 2014 Significance of interplay between austenite stability and deformation mechanisms in governing three-stage work hardening behavior of phase-reversion induced nanograined/ultrafine-grained (NG/UF) stainless steels with high strength-high ductility combination Scr. Mater. 86 60–3
[21] Mosecker L, Pierce D T, Schwedt A, Beighmohamadi M, Mayer J, Bleck W and Wittig J E 2015 Temperature effect on deformation mechanisms and mechanical properties of α high manganese C + N alloyed austenitic stainless steel Materials Science and Engineering: A 642 71–83
[22] Karaman I, Sehitoglu H, Maier H J and Chunlyakov Y I 2001 Competing mechanisms and modeling of deformation in austenitic stainless steel single crystals with and without nitrogen Acta Mater. 49 3919–33
[23] Oh B W, Cho S J, Hong S H, Kim Y G, Kim W J and Kim Y P 1994 Effects of deformation-induced twinning and martensitic transformation on the cryogenic mechanical properties of Fe-19Mn-5Cr-(0-5)Al-0.2 C alloys InAdvances in Cryogenic Engineering Materials (Boston, MA: Springer) pp 1183–90
[24] Chung J H, Jeon J B and Chang Y W 2010 Work-hardening and ductility enhancement mechanism of cold rolled multiphase TRIP steels Met. Mater. Int. 16 533–41
[25] San Martin D, Del Castillo P R, Peelstok E and Van Der Zwaag S 2007 A new etching route for revealing the austenite grain boundaries in an 11.4% Cr precipitation hardening semi-austenitic stainless steel Mater. Charact. 58 455–60