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Experimental Setup of Surface Mechanical Attrition Treatment (SMAT) and study of the treated Specimen

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Abstract: The most effective way to alter the structural properties of a material is by surface engineering. The commonly known surface treatments; such as, Nitriding, Carburizing; are expensive, but Surface Mechanical Attrition Treatment (SMAT) is a much cheaper alternative. In this paper the basic concepts of SMAT is put forth and also the effects of the treatment on mechanical properties of the material is also discussed. It was found that the hardness of the treated specimen had doubled and there was also phase transformation from γ-austenite to α-martensite The potential applications of SMAT process is also listed.

Keywords: Surface Mechanical Attrition Treatment (SMAT), Nanocrystalization, Micro-indentation, Phase Transformation

1. INTRODUCTION

Nanostructured materials have a very fine crystalline grain structure in the nanometer range. The chemical and physical properties of nanostructured materials have been observed to improve drastically compared to the same materials with larger grain sizes [1]. A novel method of grain refinement; by plastic deformation; is the SMAT process. The advantage of SMAT is that the chemical composition of the material is seldom changed. Jian LU and K. LU [2] first introduced the concept of SMAT. Conventional wisdom makes us think that nanocrystalizing the whole material results in a much more improved material than the material that is just surface nanocrystalized, but the fact is that producing a surface nanocrystalized material is practical and also results in a material with properties similar to that of the completely nanocrystalized one. Huge strides have been taken towards the research on the effects of SMAT on the properties of the material. Some of the research work has been discussed in this paper. The proposed mechanism of nanocrystalization has also been touched upon. The main material that is the focus of this paper is 316L Stainless Steel. This material has been chosen for discussion because it has a very good corrosion resistance due to the presence of 16-18% chromium.

2. SMAT SETUP

The SMAT cabin is mounted on an acrylic plate below which there is a mild steel plate. An electromagnet (2 phase, AC, 50 Hz) will be the vibration generator of the setup. The mild steel plate is attached to the electromagnet and is also supported by four springs. The SMAT cabin holds the spherical hardened steel balls. The cabin also has a grip mechanism to hold the specimen.

A schematic representation of the SMAT setup is shown in Fig.1. The vibrating chamber contains 60 to 80 hardened steel balls. When electricity is passed through the electromagnet, the electromagnet magnetizes and demagnetizes at a rate of 50Hz, because frequency of the AC current passed through the electromagnet is 50Hz. Because of this continues magnetization-demagnetization cycle the mild steel plate along with the SMAT chamber vibrates at 50Hz. This vibration accelerates the hardened steel balls toward the specimen which is placed at the top end of the chamber. The velocity of the hardened steel balls is estimated to be around 5m/s to 20m/s.

When the hardened steel balls impact the surface of the specimen at such high velocity, plastic deformation occurs on the surface. Due to this plastic deformation the surface; upto a depth of 50μm to 300μm; is nanocrystalized.

Shot-peening; which is also a similar process; is different from SMAT because in Shot-peening the angle of impact of the balls with the specimen is very close to 90˚, but in SMAT the angle of impact is random. It is because of this random angle of impact nanocrystalization is possible.

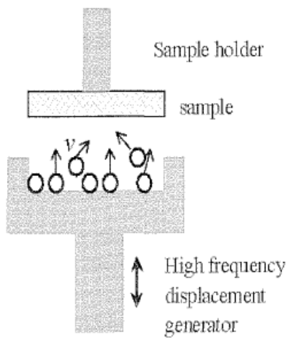

Fig 1. Schematic Representation of SMAT Setup [1]

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3. SURFACE NANOCRYSTALIZATION MECHANISM

The surface of the material which is treated by SMAT undergoes localized plastic deformation. Stainless steel 316L has a low stacking fault energy (LSFE), because of the LSFE, during the SMAT process the surface of the material undergoes twinning due to the high strain of the SMAT process. The strain is high only at the surface, it gradually reduces with increase in depth from the treated surface. Due to the reduction in strain with increasing depth, the size of the grains is smaller (in nano range) and gradually increases with increase in depth and after 60µm to 100µm depth the grain size is in the micrometer range.

The size of the grains on the SMATed surface depends on the size of the hardened steel balls used in SMAT process and the depth of nanocrystalization depends on the time duration of the SMAT process. The high-density micro twins formed due the high strain plastic deformation induced on the treated surface introduced a large amount of twin boundaries that divided the original coarse grains into Laminar Twin Matrix Alternate Blocks (LTMAB) [3]. Dense Dislocation Walls (DDW) [4] were also observed in some of the grains. These DDWs are inside the original coarse grain and are parallel to each other. These DDWs are in large numbers at the treated surface and reduce with increase in depth from the surface.

The figure below (Fig 2) shows the micro structure of 316L SS observed by an optical microscope. We can see in the micro structure that there is no significant twins visible. But when we compare this microstructure with the SMATed specimen (Fig 3), we can observe a large number of DDWs. This specimen underwent SMAT process using 5.5mm hardened steel ball diameter and for a time period of 15 minutes. We can observe that the dislocations are located inside the grain boundaries of the original coarse grains and also they are parallel to each other.

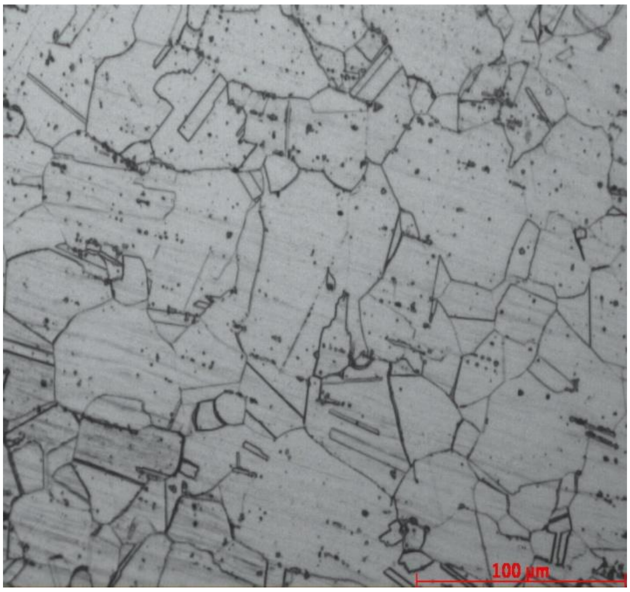

Fig 2. Optical microscopy image of 316l SS before SMAT

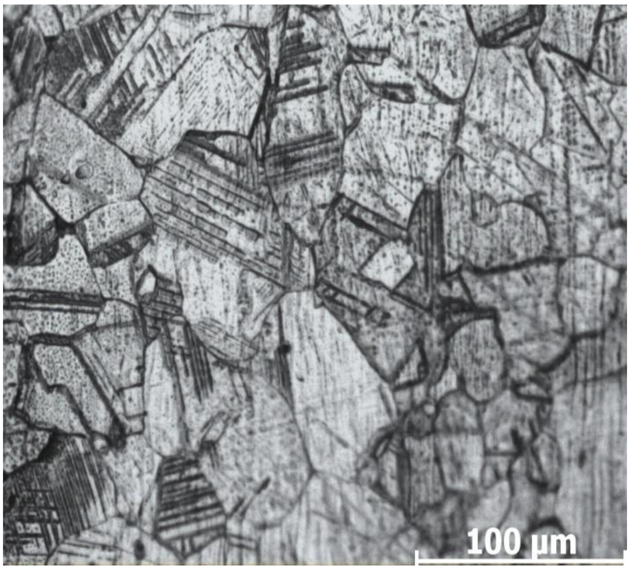

Fig 3. Optical Microscopy image of 316L SS SMATed specimen

It can be observed that the dislocations are parallel, but at some regions the dislocations are misoriented at an angle of 1˚.The spacing between the DDWs also vary form a fraction of a micron to a few microns.

The crystal size of both the treated and untreated 316L SS samples were calculated using Scherrer Formula.

$$L = \frac{K\lambda}{\beta \cos\theta} \quad (1)$$

Where, K is the crystallite shape constant, λ is the wavelength of X-Ray, β is the full width at half maximum and θ is the position of the peak.

To apply the scherrer formula we need to have the X-Ray Diffraction pattern of the specimen. It was found that the crystal size of the untreated 316L SS was 542nm and the 316L SS specimen which was subjected to SMAT process using 5.5mm diameter balls and for a time period of 15 minutes was 203. So we can see a reduction in crystal size by about 339nm. This difference will be larger for a specimen SMATed usind a larger ball size or for a longer duration of time.

4. HARDNESS

The nanocrystalized layer in the SMATed specimen is just upto a depth of 100µm to 200µm, so to access the true hardness of the SMATed specimen it is obvious to go for micro hardness. So Vicker's micro hardness is usually used to determine the hardness of the SMATed material.

It is found that hardness of the treated specimen is higher at the surface than its untreated counterpart but gradually decreases as the depth increases. This is because the effect of SMAT process and hence the size of the grains also increases. In common terms, as the grain size increases hardness decreases.

It was found that microhardness had doubled at the SMATed surface when compared with the untreated specimen, but the microhardness value reduces as the depth increases from the treated specimen and reaches the value of the untreated specimen [5].

5. PHASE TRANSFORMATION

There are two ways of martensite transformation; one is the temperature induced transformation and the second is the stress induced transformation. In SMATed specimens there is stress induced martensite transformation.

X-Ray Diffraction (XRD) was carried out using Cu $K\alpha 1$ radiation. The scanning angle range was from 20˚ to 130˚ and the step size was 0.0334˚ and the time per step was 139.700mS.

Untreated 316L SS specimen was γ-austenite but after SMAT process there was a partial phase transformation to α-martensite. The new peaks generated in the XRD pattern of the treated specimen are the α-martensite peaks [6]. The miller indices of the two new peaks are (110) and (211).

The volume fraction of α-martensite was 0% for the untreated specimen while the treated specimen had a α-martensite percentage of 4%.

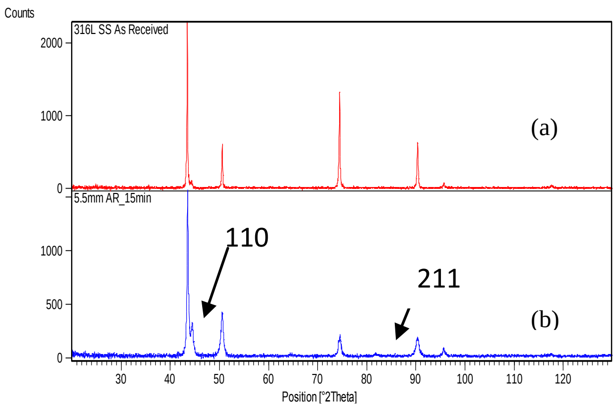

Fig 4. X-Ray Diffraction Pattern of untreated 316L SS (a) and SMATed 316L SS (b) for 15 min using 5.5mm ball diameter

6. APPLICATIONS

It is proved thus far that SMAT process produces a nanocrystalized surface without affecting the chemical composition of the material. It does not affect the magnetic of electrical properties of the material as well.

It is also observed that many mechanical properties; like hardness, fatigue strength; of the material is also improved by this treatment. Using this process of grain refinement is also practical in terms of economy and ease of processing.There are a variety of application for this process, such as treatment of the steel sheets used in manufacture of pressurized tanks. These tanks undergo fatigue as they are pressurized and depressurized, so my SMAT treating these sheets the tanks can withstand more number of these pressurization-depressurization cycles. Same applies to aircraft cabins, because these cabins are pressurized and depressurized every time they land or takeoff. So, by SMAT process the cabin can be reinforced to withstand more number of cycles.

316L SS which is naturally corrosion resistant because of the presence of 16% to 18% of chromium is proposed to be used in surgical implants. When it is used as surgical implants, it undergoes corrosion fatigue, so if SMAT is used as a process for grain refinement, the implants can withstand a lot more cycles.

The elevators, radars, ailerons in aircrafts ate attached to the frame of the aircraft using hinges, because they should be allowed to pivot. These hinges undergo huge amount of stress as they allow the radars and elevators to move during flight. Environmental factors also contribute towards corroding these hinges. So if SMAT is used these drawbacks can be overcome.

7. RESULTS

It was found that SMAT process is an economical and practical method of surface grain refinement method. It is also established that the surface nanocrystalization mechanism for materials with LSFE is by mechanical twinning.

Micro hardness of the materials also shoots up after SMAT process, but only at the surface and reduces with increase in depth until finally reaching the same value of the untreated material. Grain refinement is done only on the treated surface upto a certain depth, but this can influence the mechanical behavior of the entire material because the cracks and pits are initiated at the surface of the material, so by refining this portion these defects can be controlled.

It is also concluded that there is a stress induced α-martensite phase transformation after SMAT process. This also contributes towards improving the hardness of the SMATed material.

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