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FATIGUE PROPERTIES OF SMOOTH AND AS-SHOT PEENED N BEARING AUSTENITIC STAINLESS STEEL UNDER TENSION-TENSION CONDITION

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ABSTRACT

The fatigue properties of solution treated (ST) high nitrogen austenitic stainless steel (RS561) have been compared with a commercially available standard austenitic stainless steel (SUS310S) before and after shot peening. For doing this tension-tension fatigue tests were carried out at 5Hz and 22Hz frequencies at room temperature in air. In order to know the shot peening effects, half of the specimens of both steels were shot peened (SP). As per the experimental results, addition of nitrogen significantly improves the fatigue life and changes the fatigue fracture morphologies of the stainless steel, whereas frequency was found to have no marked effect on the fatigue lives. Shot peening have been found to increase the fatigue limits and change the fracture mechanisms of both steels. However, the increase in the fatigue limit in high nitrogen steel is much lower than that of the SUS310S steel. At high applied stress levels, effect of shot peening was found to disappear for both steels.

Keywords: High nitrogen steel, Tension-tension fatigue, Frequency, Shot peening, Fracture morphologies.

INTRODUCTION

Higher carbon content in the austenitic stainless steel (SS) may cause Cr-rich carbide precipitation and the Cr content in the vicinity of grain boundaries decreases and causes intergranular corrosion cracking in the corrosive environments. If the carbon content is reduced, then this sort of problem decreases significantly. However, lower C content in this SS steel reduces the yield strength and consequently limits their applications. As an alloying element nitrogen is very effective to improve the mechanical properties and corrosion resistance of stainless steels and thus nitrogen addition into stainless steel has become very popular [1-3]. Because of many beneficial effects, e.g., better mechanical properties and corrosion resistance, reduction in expensive alloying element Ni as well as Ni-induced allergy in human body and so on, the demand of high nitrogen stainless steels is increasing day by day. Addition of nitrogen increases the yield and tensile strength of austenitic stainless steels without decreasing the ductility and toughness [4-5]. Addition of nitrogen also improves the fatigue life of stainless steel [1-3]. An Addition of nitrogen in the austenitic steel causes the formation of planar dislocation arrays [4-6]. Moreover, during cyclic loading, hardening is also promoted by the formation of dislocation subcell structures providing prolonged number of cycles to rupture [7].

Shot peening has been used for many years as a most versatile pre-stressing process for strengthening metal machine parts against stress corrosion and fatigue failure by producing compressive residual stresses [8,9]. In this study, the tension-tension fatigue tests have been carried out at room temperature in the air to know effect of nitrogen additions on the fatigue life and fracture behaviors of austenitic stainless steel before and after shot peening. For a comparative study, commercially available austenitic stainless steel was also used as a reference material. Using limited number of samples, initiative has also been taken to investigate the frequency effect on the fatigue lives of high nitrogen SS.

EXPERIMENTAL PROCEDURES

The steel for the present research study was a high nitrogen austenitic steel (RS561) and a commercially available standard (no added nitrogen) austenitic stainless steel (JIS-SUS310S). The later was used as a reference steel for a comparative study to know the effects of nitrogen addition and shot peening on the fatigue behaviors of austenitic stainless steel. The compositions of these two steels are given in Table-1.

Table-1. Chemical composition of the steels used (Mass%).

Element	SUS310S Steel	RS561 Steel
C	0.04	0.02
Si	0.72	0.15
Mn	1.08	6.0
P	0.024	---
S	0.002	---
Ni	19.01	10.0
Cr	24.93	23.0
Mo	---	2.0
V	---	0.14
N	0.039	0.48

Fatigue specimens having geometry given in Figure-1 were prepared from both steels in the solution treated condition (3.6ks at 1273K for RS561 steel and 1.8ks at 1373K for SUS310S steels) and polished

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properly. Some of the polished specimens of both steels were then shot peened under similar condition to modify the surface properties and they were marked as shot peened (SP) specimens. The shot peening conditions employed were: 0.6mm diameter spherical steel particles, 1.0mA arc height and 300% coverage. Before shot peening, the specimen will be denoted as smooth or un-shot peened (USP) condition.

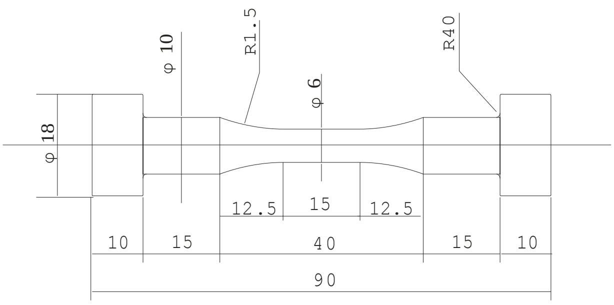

Figure-1. Geometry of the fatigue specimen.

The fatigue tests were carried out under tension-tension condition at room temperature in the air. To have the *S-N* curve, tests were performed at different initial stress levels. After fatigue failure, specimens were cut behind the fracture surface to have the specimens suitable for fractographic observation in the SEM. In the SEM, various fracture features such as fatigue crack initiation sites, fracture mode, striation marks, etc. were observed carefully and they were photographed. In order to explain the fatigue results, Vickers hardness measurements were carried out from surface towards the core of both steels in the SP condition and tensile tests were carried out on smooth specimen. Using X-ray and neutron diffraction techniques the residual stress on the surface of RS561 steel in the SP condition was also carried out.

RESULTS

Residual stress, hardness and tensile properties

Concerning the residual stress in the shot peened specimens X-ray and neutron stress measurements were performed. It was found that the maximum compressive residual stress on the surface RS561 steel after shot peening was approximately 1.0GPa and the depth corresponding to the high residual stress was about 0.5mm [10], which is also clear from the hardness profiles presented in Figure-2.

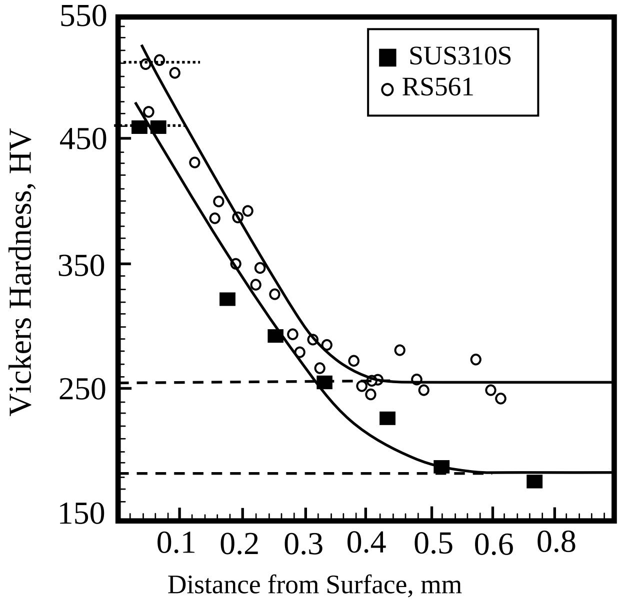

Figure-2. Hardness distribution of RS561 and SUS310 steels in the SP condition.

From these hardness profiles, it was evident that the hardened zone of RS561 steel was somewhat narrower compared to that of the SUS310S steel. The initial average surface hardness values of RS561 and SUS310S steels were, respectively, 255HV and 180HV, which were subsequently increased, respectively, to 510HV and 460HV after shot peening. The nominal stress-strain curves of smooth specimens of both steels are presented in Figure-3. This figure reveals that addition of nitrogen significantly increased the yield and ultimate tensile strengths of the steel without compromising the elongation.

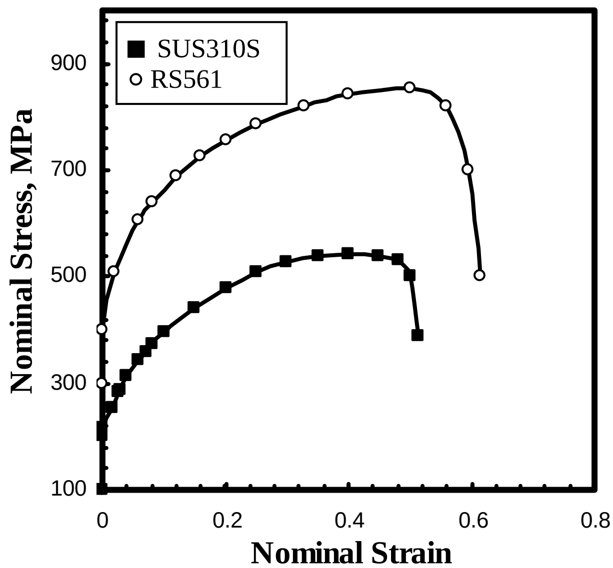

Figure-3. Nominal stress-strain curves of USP RS561 and SUS310 steels.

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Fatigue life

Smooth specimens (USP Condition)

High nitrogen austenitic stainless steel (RS561) exhibited much better fatigue performances at any applied stress level, which is clear from Figure-4. The fatigue limit of RS561 is corresponding to 194MPa stress level, which is about 34% higher than that of the SUS310S steel. An important observation is that there is a little frequency effect (between the two frequencies considered in the present study) on the fatigue lives of RS561 steel. As little frequency effect was observed on RS561 steel, it was not continued on SUS310S steel.

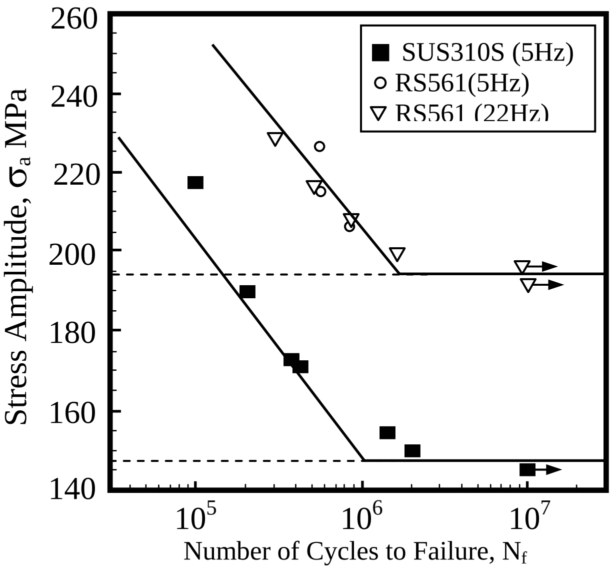

Figure-4. S-N curves of SUS310S and RS561 steels in the USP condition.

Shot Peened Specimens (SP Condition)

The effect of shot peening on the fatigue strength of SUS310S steel is presented in Figure-5.

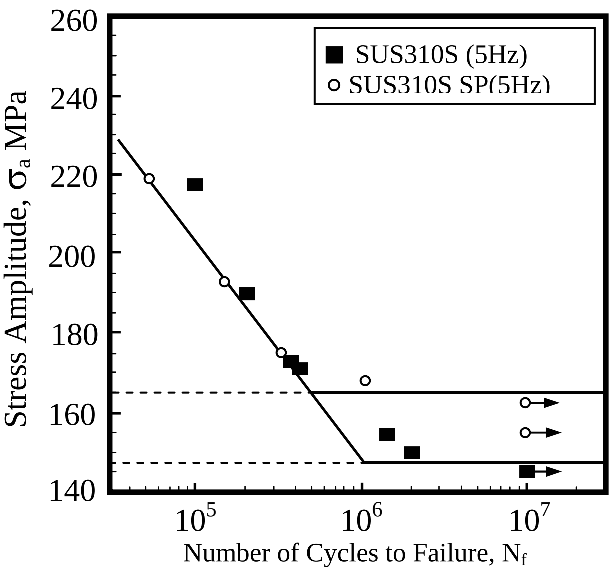

Figure-5. S-N curves of SUS310S steel showing the effect of shot peening on fatigue strength.

This figure reveals that shot peening resulted about 12% higher fatigue limit of the steel. However, when the applied stress is increased above the fatigue limit of the SP steel, then no shot peening effect on the fatigue life is observed. In such case, the fatigue lives of SP and USP, i.e., the smooth specimens became indistinguishable. The high nitrogen bearing steel also showed the similar behavior to that of SUS310S steel, which is clear from Figure-6. But, the improvement in fatigue limit due to shot peening is not as pronounced as that for the SUS310S steel. In this case only about 5% increase in the fatigue limit is observed, which is about 12% for the reference steel.

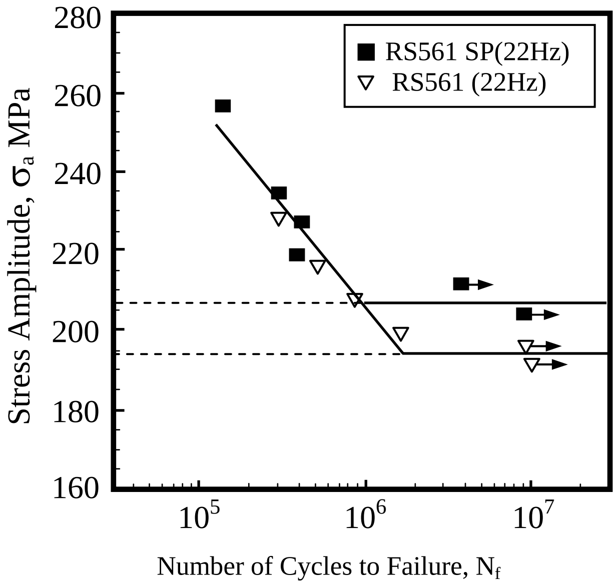

Figure-6. S-N curves of RS561 steel showing the effect of shot peening on fatigue strength.

Fractographic Observation

USP Condition

Before shot peening, both steels exhibited mixed mode (transgranular cracking and microvoid coalescence type ductile fracture). However, ductile microvoid coalescence type fracture is more dominating in SUS310S steel, which is very clear from the fractograph presented in Figure-7a. In this case, microvoids are observed not only at the centre but also close to the surface from where fatigue microcracks started to propagate (marked by arrows) inside the specimen. At high magnifications, striation marks are clearly seen inside these microvoids, Figure-7b, which reveals that voids were started around inclusion particles and grown to some extent by the action of cyclic loading. From low magnification fractograph of smooth specimen of RS561 steel presented in Figure-7c, apparently it seems that there is no ductile microvoid, however, at a somewhat higher magnification this fracture feature is clearly observed, Figure-7d. More characteristic features of

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RS561 steel before shot peening are presented in Figures-8a and 8b.

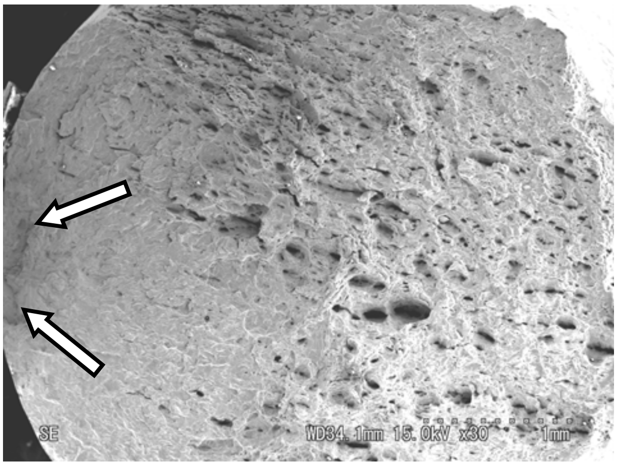

Figure-7a. SEM micrograph in USP condition. Overall fracture features of SUS310S at stress amplitude of 219MPa and numbers of cycles to failure 99391. Arrows are indicating the inclusion-nucleated cracks near the surface of SUS310S steel.

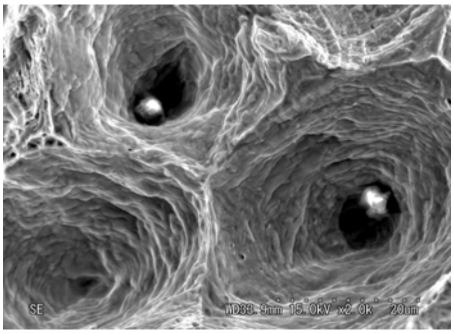

Figure-7b. SEM micrograph in USP condition. Crack growth around inclusion particles on Fig.7a.

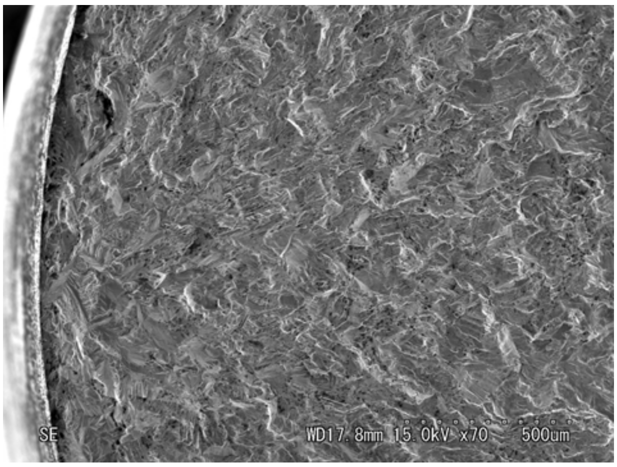

Figure-7c. SEM micrograph in USP condition. RS561 steels at stress amplitude of 219MPa and numbers of cycles to failure 527726.

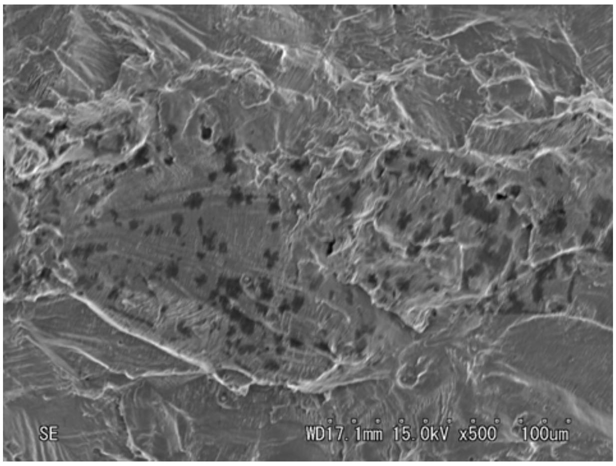

Figure-7d. SEM micrographs in USP condition. Close-up view of inclusion nucleated voids on Fig.7c.

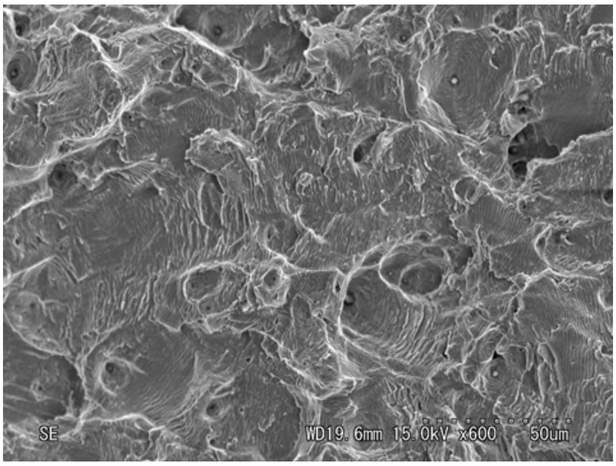

Figure-8a. SEM micrograph showing inclusion nucleated many voids along with distorted striation marks of USP RS561 steel at stress amplitude of 219MPa and a number of cycles to failure 527726.

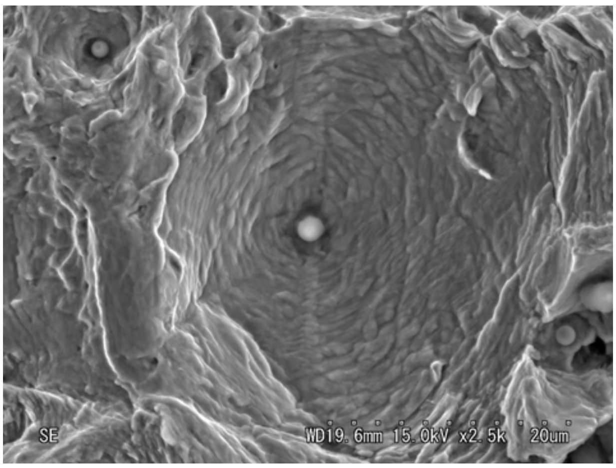

Figure 8b. SEM micrograph showing striation marks around an inclusion.

SP Condition

After shot peening, the fracture morphologies of both steels drastically changed. Except some isolated voids on SUS310S steel (marked by arrows), the ductile microvoid coalescence type fracture became almost absent, Figure-9a. Fracture surface of RS561 steel in SP condition is smoother and brittle fracture is more dominating compared to the reference steel, Figure-9b. Now, the river patterns of fatigue crack propagation became more evident on fractographs of both steels. This feature clearly indicates that cracks were initiated first from the surface and then propagated inside the specimen.

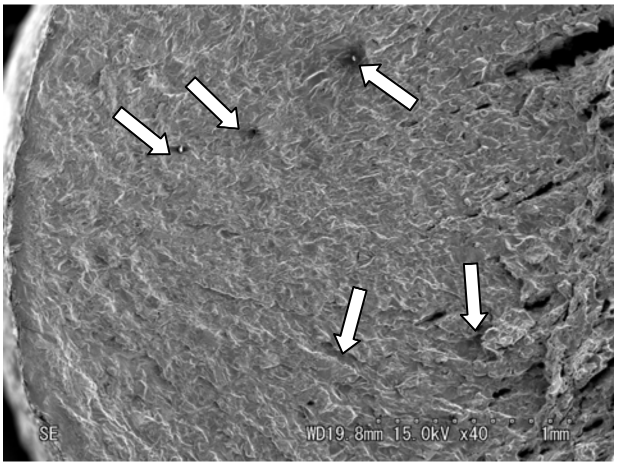

Figure-9a. SEM micrograph showing the fracture features of SP specimens. SUS310S steel at a stress amplitude of 171MPa and numbers of cycles to failure 344001. Arrows are indicating the inclusion nucleated microvoids.

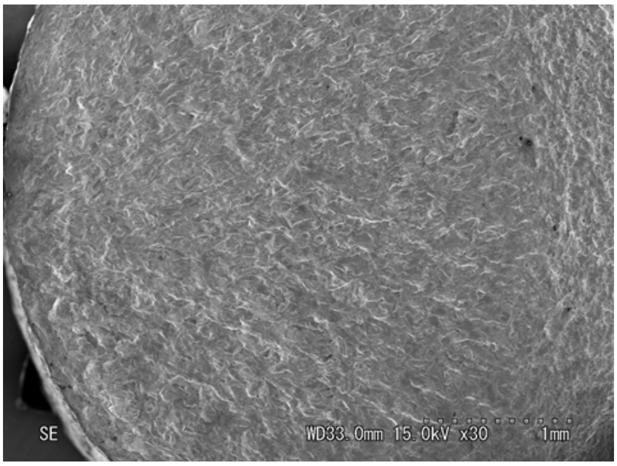

Figure-9b. SEM micrograph showing the fracture features of SP specimens. RS561 steel at stress amplitude of 207MPa and numbers of cycles to failure 718827.

DISCUSSION

From the previous section it is clear that, before shot peening, high nitrogen bearing austenitic stainless steel has much better fatigue life than that of the standard austenitic stainless steel. Shot peening only increased the fatigue limits for both steels, but at higher stress levels its effects disappeared. Experimental results also revealed that fatigue lives at 5Hz and 22Hz frequencies are almost the same. Another important point to be mentioned is that increase in the fatigue limit in RS561 steel due to shot peening is not as significant as observed in the case of SUS310S steel. Shot peening also changed the fracture morphologies for both steels. Now all these observations will be discussed below.

At first consider the better fatigue life of high nitrogen steel in the UPS condition. In the case of high nitrogen steel, the nickel content is reduced, however, significantly higher amounts of manganese, molybdenum and nitrogen have been added. These additions increased the strength of the steel significantly (see Figure-3). Higher tensile and yield strength of the steel make the crack nucleation difficult. As long as the crack nucleation is delayed, the better will be the fatigue life. So, high nitrogen steel showed better fatigue life. Similar observation has also been mentioned by other investigators [1,11]. The change in the mechanical response due to nitrogen addition can also be explained on the basis of the dislocation structures. The most noticeable effect of nitrogen is to induce planar glide of the dislocations thus inhibiting cross slip. An example of dislocation structure developed during fatigue of $8.3X10^5$ cycles at 208MPa is presented in Figure-10a. Below the ductile-brittle-transition temperature (DBTT), the (111) plane separation takes place in high N bearing steel (12). As fatigue fracture is a brittle type of fracture, fatigue fracture surface of RS561 steel in SP condition also exhibits the characteristic feature of the brittle fracture, Figure-10b.

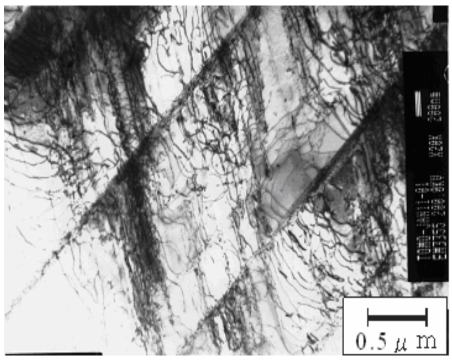

Figure-10a. TEM micrograph of RS561 steel cyclically deformed at a stress amplitude of 208.43MPa for $8.3x10^5$ cycles.

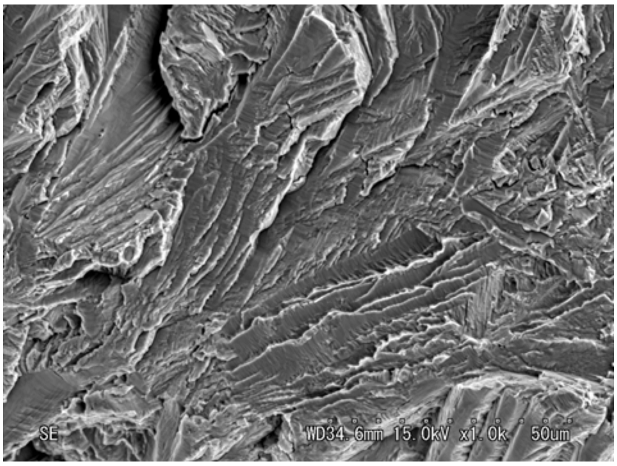

Figure-10b. TEM micrograph of RS561 steel. Characteristic feature of the brittle fracture in high nitrogen bearing steel.

After shot peening, high nitrogen steel showed better fatigue limit compared to that of the SUS310S steel, however, the improvement in fatigue limit is not as encouraging as that for the latter and that at higher stress levels the positive effect of shot peening does not exist for any steel. The shot peening produced the residual stress of 1.0GPa at the surface and work hardening in RS561 is very high (see Figure-2). To explain these phenomena, let us consider the schematic diagrams presented in Figures-11a and b.

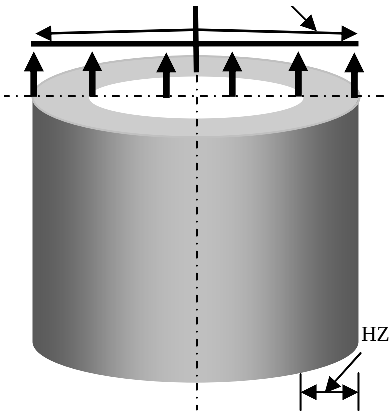

Figure-11a. Schematic diagram showing the stress distribution under tension-tension conditions. HZ denotes hardened zone.

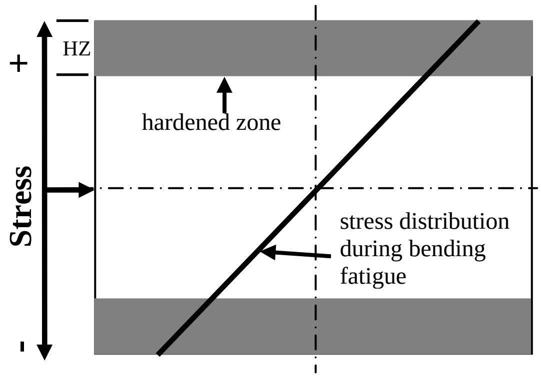

Figure-11b. Schematic diagram showing the stress distribution under bending conditions. HZ denotes hardened zone.

For fatigue properties, the geometry of test piece and test conditions are very important. In the pull-pull fatigue test, the load is accommodated across the full section of the specimen and thus the presence of the stress raisers at surface is less critical compared to that of fatigue test under bending condition [13]. In this case, specimen centre is the most critical part to nucleate the crack (provided that the stress raisers at surface and in the core are of similar severity) because of more effective stress tri-axiality effect at the specimen centre. Due to this stress tri-axiality, crack initiation takes place first from inside of the smooth specimens rather than from the surface. In the bending fatigue test the opposite is the stress distribution and thus the crack nucleation starts from the surface [14,15]. In this present study similar fracture morphologies that are expected have been observed. Cracks have been found to nucleate from many inclusions remained distributed throughout the whole cross-section, Figure-7. Fatigue crack initiation is also brought by carbide particles, although most of microcracks in smooth specimens of the present study are inclusion nucleated. We know that specimen centre is the most critical portion to nucleate microcracks in the tension-tension fatigue condition, however, if by accident a significantly coarse non-metallic inclusion and/or carbide particle remain at surface or sub-surface region, and then crack nucleation can also take place by them, which is clear from Figure-7a. Because, on the basis of balance between size and shape of inclusions and distance from the most critical region, inclusions located at the surface or subsurface can also satisfy the condition for crack nucleation. As a result, crack has been found to nucleate at many locations from subsurface towards the centre of the specimen, Figure-7a. As the fatigue cracks did not nucleate from a single point, the river patterns of crack propagation was not so well-defined for most of the USP specimens. After nucleation, these cracks grew from different locations following cyclic loading by very much ductile fashion. The ductile crack growth from inclusion nucleated cracks with cyclic loading is very clear from the deformed striation marks in the voids around the inclusions, Figures-7b and 8b.

For the SP specimens of both steels, the fatigue limits are increased keeping the fatigue lives at higher stress levels very similar to that of USP specimens. Typical characteristics of SP surfaces are compressive residual stresses and extremely high dislocation densities in near surface layers. The high compressive residual stress in the hardened zone distinctly reduces the effective stress under loading as long as it exists in the structure. This is generally considered as the reason for delayed crack nucleation and propagation of the newly formed cracks during cyclic loading or arresting the preexisting cracks formed during manufacturing/ processing routes [7,16]. In the present study shot peening has been found to damage the surface by forming sharp cracks of different sizes as shown in Figures-12a and b. In contrast, many inclusions were found in the worst case of smooth specimen (Figure-12a), which is less severe as stress raiser compared to that of sharp cracks on SP specimens. Because, inclusions usually induce spherical and relatively smoother type of holes or defects. Experimental results suggest that the positive effect of compressive residual stress and higher strength caused by shot peening can delay the crack propagation of the preexisting microcrack up to a certain higher stress only compared to that of the smooth specimens. This is probably due to compromise between the positive effect of compressive residual stress and negative effect of pre-existed sharp crack on specimen surfaces. As a result, the fatigue limits of SP specimens of both steels increased to some extent. As pre-existing surface cracks are much more severe stress raisers in the case of bending fatigue and tensile stress is mainly responsible for crack growth, the fatigue performance of the SP specimens could be such that there is no increase in the fatigue life, even that the resulted fatigue life could be lower compared to USP specimen in the bending fatigue condition.

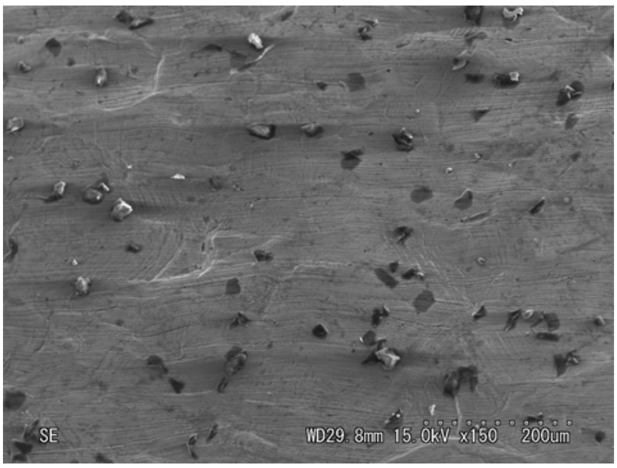

Figure-12a. Micrograph showing the surface topography of RS561 steel, smooth specimen.

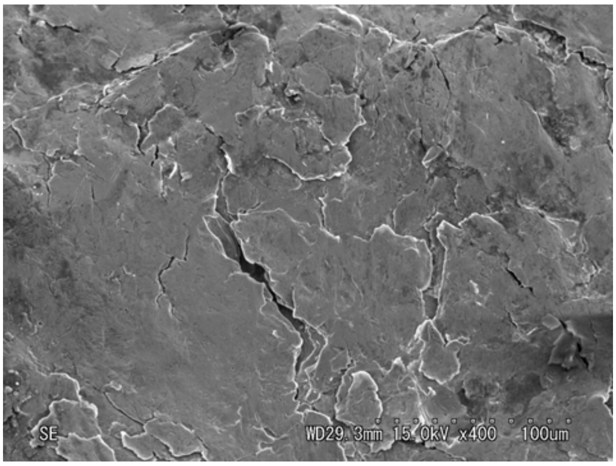

Figure-12b. Micrograph showing the surface topography of RS561 steel; shot peened specimen.

Now the question why shot peening is not inducing any better fatigue life at higher applied stress levels of that of fatigue limit. In this section, the possible reasons behind this will be discussed. In the SP specimens, at high stress amplitudes, the initially heavily tangled dislocation distributions can be united in a few cycles, whereas at low stress amplitudes the initial dislocation arrangements remain more or less stable [9] with cyclic loading. As a result, for high stress levels, release of compressive residual stress takes place very quickly. This means that the beneficial effect of compressive residual stress to delay the crack nucleation or arrest of the pre-existing microcrack propagation gradually disappears. At this situation, under cyclic loading, stress concentration at the tip of the sharp pre-existing microcracks formed on the specimen surfaces during shot peening encourages them to grow and propagate well before the nucleation of microcracks around the inclusion particles inside the specimen (that happened in the case of USP specimens). The surface cracks just behind the fracture surface are shown in Figure-13a. Propagation of these surface cracks inside the matrix is also clear from Figure-13b. As the surface layer of SP specimens are harder compared to that of USP specimens, the fatigue cracks penetrate inside the specimen easily maintaining brittle fracture behaviors to be dominating. As a result, at high stress levels, the micromechanisms of fatigue crack formation as well as propagation in the SP specimens have been changed, which is responsible for their unexpected fatigue lives.

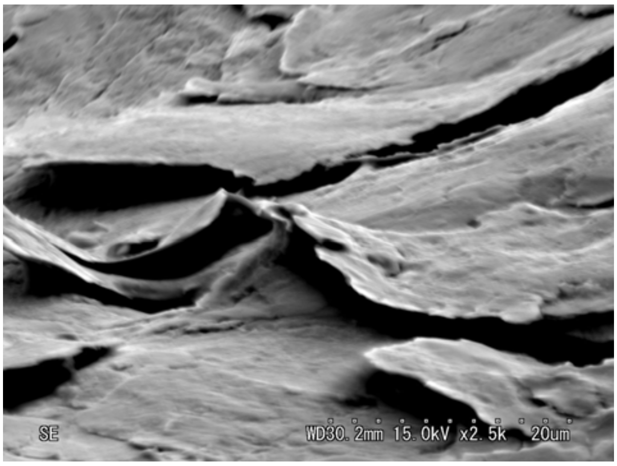

Figure-13a. SEM micrograph showing microcracks size on surface of SP specimen of RS561 steel after fatigue test at a stress amplitude of 207MPa and numbers of cycles to failure 718827.

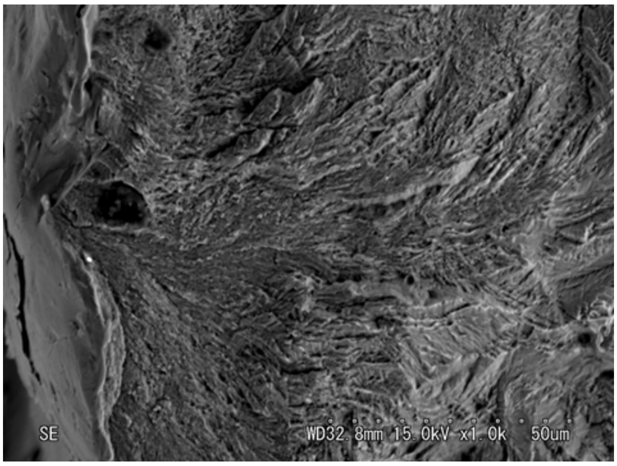

Figure-13b. SEM micrograph showing surface crack propagation inside the specimen.

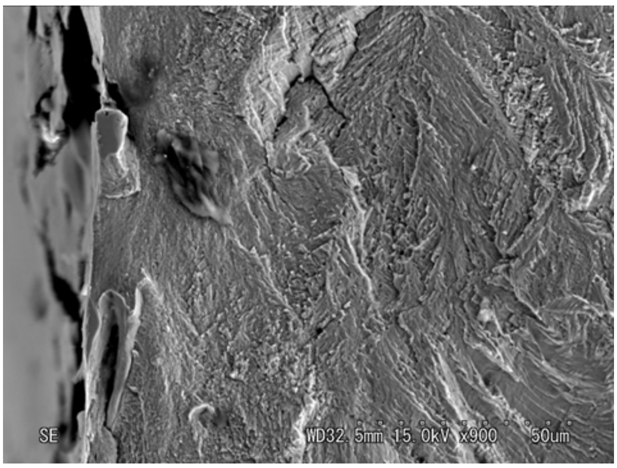

Figure-13c. SEM micrograph showing surface crack propagation inside the specimen.

In the case of SAE 1045 steel in SP condition Martin et al. [9] also mentioned similar results. In their study, it has been mentioned that the initial residual stresses due to shot peening have entirely disappeared after half of the fatigue lives under cyclic loading at stress amplitudes of 350-450MPa. Only the lowest stress amplitude (stress level close to the fatigue limit which is about 300MPa) has not changed the initial residual stress depth profile significantly, Figure-14. For high strength martensitic steel, Eleiche et al. [8] also mentioned very similar observation. At stress levels higher than that of fatigue limits, they found no improved fatigue lives. Here it is to be mentioned that Martin et al. [9] used the shot peened specimens after polishing, i.e., some of microcracks were eliminated during polishing and the severe effect of stress concentration might be reduced to some extent. Under this condition, they found the increase in the fatigue limit due to shot peening by more than 20%, which is only 12% for SUS310S steel and 5% of the RS561 steel in the present study. For high strength martensitic steel, Eleiche et al. [8] also found similar results. In their study, the increase in fatigue limit was about 21% after shot peening and mechanical polishing to within 0.02mm.

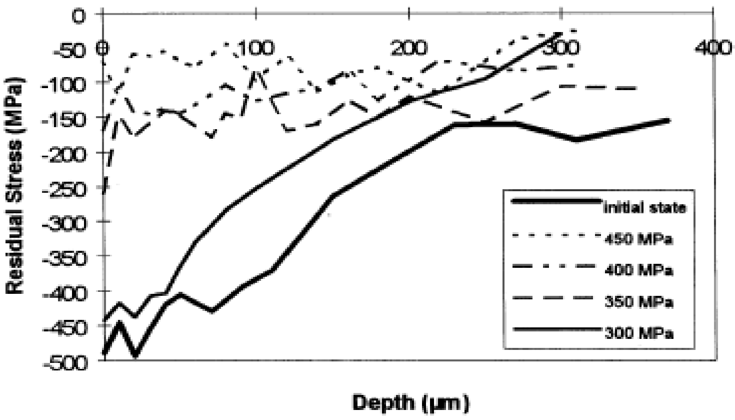

Figure-14. Stress relaxation of SP SAE 1045 steel during fatigue after half the number of cycles to failure (After Ref. [9]).

In the previous section, it has been mentioned that compared to 12% increase in the fatigue limit in SUS310S steel, shot peening increased the fatigue limit of RS561 steel only by 5%. We know that addition of nitrogen and other alloying elements increased the hardness and strength of RS561 steel. As the hardness of specimen increases, the chance for microcrack formation during shot peening also increases. Moreover, the cracks will be sharper on a harder specimen. However, on a soft specimen, e.g. on SUS310S specimens, microcracks will plausibly more blunted. Blunted cracks mean less severe is the stress concentration on the specimen surface if they are loaded. As a result, the crack growth from the pre-existing blunted microcracks took somewhat longer period of time to grow inside the specimens. Due to this surface condition and crack growth behaviors in

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SUS310S steel, there was better improvement in fatigue limit in this steel compared to that of the RS561 steel after shot peening.

Another very interesting observation is that the striation marks on SP specimen are sharper and the voids around inclusions are also smaller compared to that of smooth specimen (USP specimen). This is because microcracks formed during shot peening started to propagate well before the inclusion nucleated microcracks and thus the latter got lower time to grow before final fracture. The well-defined river pattern from crack nucleation regions of SP specimens presented in Figure-9a and very isolated and smaller inclusion nucleated microvoids also suggest the earlier crack propagation from surfaces of the SP specimens. Striation marks on the fracture surfaces are very important and characteristic features of fatigue fracture. The nature of striation marks on micrographs presented in Figures-8b and 15a also suggest that inclusion-induced microcracks in smooth specimens were formed earlier that of the SP specimen. In both specimens, the strength of core is almost the same so inclusion-induced microcracks might experience similar resistance from surrounding materials during growth. However, the voids in smooth specimen are much larger compared to that of the SP specimen and the striation marks are somewhat distorted, Figures-8a and 15a.

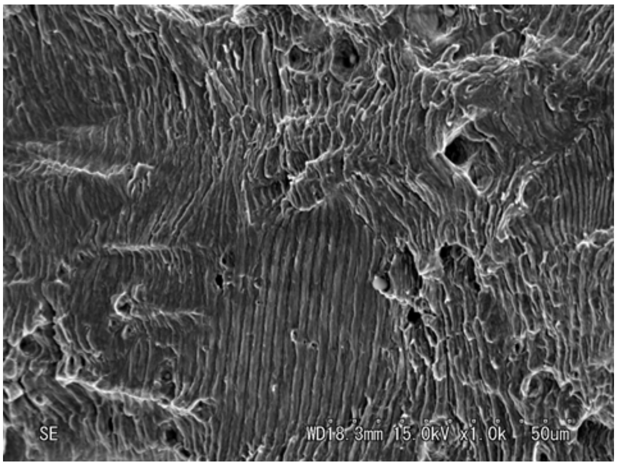

Figure-15a. Striation marks on SP specimen of RS561 steel after fatigue fracture at a stress amplitude of 202.5MPa and cycles to failure 4750569.

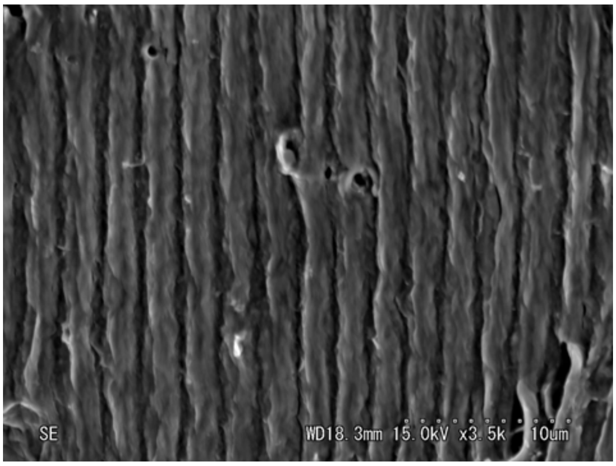

Figure-15b. Close-up view of Figure-15a.

In this study, results on limited specimens exhibited that there is no significant difference between the fatigue lives associated with frequencies 5Hz and 22Hz. Many investigators have studied the frequency effects on the fatigue lives of differents materials. Working with 316N stainless steel, Tian et al. [17] mentioned that test frequencies up to 20Hz are generally not capably to raise specimen temperature and thus no softening and deterioration in fatigue life is expected. For pressure vessel steel, Liaw et al. [18] found about 95^{o}C increase in temperature of the test piece at 1000Hz frequency, however, at 20Hz, the test piece temperature was only about 23 to 24^{o}C, which is usually the room temperature in most cases. Working with AISI-SAE 52100 steel at frequencies 20, 30 and 35Hz frequencies at room temperature in the air, Marines et al. [15] found no change in fatigue life. Furuya et al. [14] and Strizak et al. [19] also made similar comments.

CONCLUSION

From the fatigue test results under tension-tension condition at room temperature in the air and fractographic observations of the failed specimens of SUS310S and RS561 steels before and after shot peening, the following conclusions are made.

1. Addition of nitrogen significantly improves the fatigue lives at all stress levels used in the present investigation and also changes the fatigue fracture mechanisms. In the case of high nitrogen austenitic stainless steel the brittle fracture is mainly transgranular type whereas both brittle transgranular and ductile microvoid coalescence type crack growths have been found for SUS310S steel.

2. Shot peening improves the fatigue limits of both steels, however, the fatigue lives at any stress higher than the stress levels corresponding to the fatigue limits remain unchanged for both steels.

3. Shot peening causes further change in the fatigue fracture behaviors. In the case USP specimens, nucleation of inclusion induced internal ductile cracks and their growth have been found to play more dominating role for the final fracture. However, in SP specimens, preexisting microcracks on surfaces have been found to grow under cyclic loading well before the formation of inclusion nucleated cracks inside the specimen and thus played the dominating role for final fracture.

4. The increase in fatigue limit of SP high nitrogen steel is not as encouraging as that observed for the SUS310S steel. Microcracks formed on the specimen surfaces of high nitrogen steel during shot peening have been found to act as more effective stress raisers than the inclusions.

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