TECHNICAL PAPER

Effect of Ultrasonic Shot Peening on Surface Microstructure and Fatigue Behavior of Structural Alloys

Vakil Singh[1] · Vaibhav Pandey[1] · Sanjeev Kumar[1] · N. C. Santhi Srinivas[1] ·
Kausik Chattopadhyay[1]

Abstract Fatigue resistance of structural materials is considered as one of the most important factors in design of structural components for integrity, efficiency and safe functioning under repeated mechanical/thermal loading. Fatigue resistance of structural alloys is characterized in terms of appropriate parameters based on high cycle/low cycle fatigue loading. Fatigue life comprises of two components, number of cycles for crack initiation and for crack propagation. While there is dominant role of the process of crack initiation in high cycle fatigue, low cycle fatigue is controlled by crack propagation. Invariably, fatigue cracks initiate from the surface and surface modification has been used for enhancement of fatigue life, delaying the process of crack initiation. Inducement of compressive residual stress in surface region through shot peening has been one of the most widely used conventional process of enhancing high cycle fatigue life. This paper presents the effect of surface grain refinement, using the novel technique of ultrasonic shot peening, on enhancement of fatigue life of structural alloys at low stress/strain.

Keywords Ultrasonic shot peening · Nanostructure · Tensile · Fatigue · Corrosion

1 Introduction

The process of ultrasonic shot peening (USSP) was perceived in the late 90's as a novel technique of surface modification for improving the resistance of structural components against surface related phenomena like fatigue, corrosion and wear. It was observed that surface region of iron was refined to nano size crystallites and its properties were considerably improved. Later, this technique was used for refinement of surface grains of several metals and alloys and various properties were found to be enhanced [1–4]. Transmission electron microscopy was used to characterize the microstructure of surface region of the specimens subjected to USSP, layer by layer, and it was established that there was not any sharp interface between the modified surface layer and the substrate. Further, chemical composition of the material is not altered. Several studies have been carried out on various mechanical properties such as hardness, tensile, wear, fatigue and also corrosion behavior of different metals and alloys, following USSP. It was observed that there was considerable improvement in these properties.

The effect of shot peening in improving fatigue resistance of structural components like gears, cams and camshafts, springs, connecting rods, crankshafts, and turbine blades has been quite old and based on creation of compressive residual stress in the surface region. However, the concept of surface modification through USSP for improving surface related properties is based essentially on refinement of surface grains.

This paper deals with the process of USSP and its effect on grain refinement in surface region and on mechanical properties like micro hardness, tensile and fatigue of important metals and alloys like aluminium and its age

✉ Vakil Singh
vsingh.met@itbhu.ac.in

[1] Department of Metallurgical Engineering, Indian Institute of Technology (Banaras Hindu University), Varanasi 221005, U.P., India

hardening alloys, iron and steels, superalloys, titanium and titanium alloys.

2 The Process of Ultrasonic Shot Peening

Ultrasonic Shot Peening is based on impingement of spherical steel balls on surface of the component, using ultrasonic waves. The balls are placed in a reflecting chamber that is vibrated by a vibration generator. Typical ball sizes are 1–3 mm in diameter, however, they could also be of larger size. The vibration frequency of the chamber is 20 kHz. When the balls are resonated, the surface of the sample to be treated is impacted by a large number of flying balls over a short period of time. The impact directions of the balls onto the sample surface are random. Each impact induces plastic deformation with a high strain rate in surface region of the sample, as shown schematically in Fig. 1. As a consequence, the repeated multidirectional impacts at high strain rates onto the sample surface result in severe plastic deformation and grain refinement progressively down to the nanometer regime in entire surface of the sample [5].

In contrast to the conventional process of shot peening, balls of much larger size with smooth surface are used in surface mechanical attrition treatment (SMAT). In SMAT, impacts of balls are rather random in contrast to that in the process of conventional shot peening, in which the angle between the shot jet and the surface is normally fixed close to 90°. Surface nano structuring can also be achieved using other techniques like laser shock peening [6, 7], hammer peening [8, 9], surface rolling [10], ball drop [11, 12] and high speed drilling [13]. The thickness of nano structured surface layer varies with applied strain and strain rates.
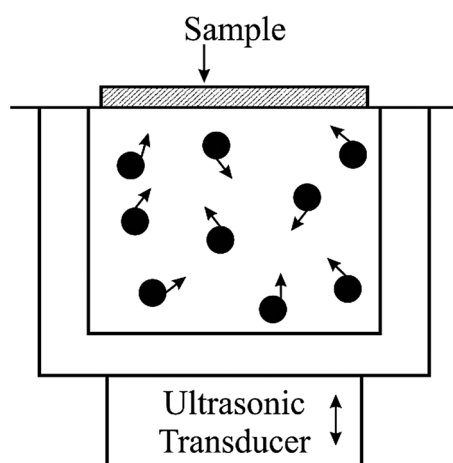

Fig. 1 Schematic illustration of the surface mechanical attrition treatment set-up

3 Effect of Ultrasonic Shot Peening on Surface Microstructure

It is important to understand the mechanism of surface nano structuring from ultrasonic shot peening. Due to gradient in strain and strain rate from the treated surface to substrate, a gradual increase occurs in grain size, from a few nanometers to several micrometers without any sharp interface. Several studies have been carried out to characterize the modified microstructure from surface to substrate in different metals and alloys [14–22]. The plastic deformation and dislocation activities in metals and alloys strongly depend on their crystal structures and stacking fault energy (SFE).

Broadly, grain refinement mechanisms of metals are categorized based on their SFE. In metals with high SFEs, dislocation walls and dislocation cells are developed to accumulate strains and consequently sub-boundaries are formed on further straining to subdivide the coarse grains. On the other hand in metals of low SFEs, plastic deformation mode may shift from dislocation slip to mechanical twins under high strain rate and low temperature. Iron is a metal with high SFE of about 200 mJ/m^2 [5]. Firstly formation of dense dislocation walls (DDWs) and dislocation tangles (DTs) occurs and subsequently these DDWs and DTs transform into sub-boundaries and get divided into smaller grains. Further straining leads to formation of nanostructure with high misorientation. Copper is a metal with medium SFE of about 78 mJ/m^2 [19]. Initially evolution of dislocation cells (DC) occurs in the deformed region with low strain rates and mechanical twinning results in some grains at favorable orientations. On further straining, DCs transform into sub boundaries with small misorientations and twin boundaries divide the coarse grain into ultrafine structure. AISI 304 stainless steel has very low SFE of 17 mJ/m^2, instead of DDWs as in iron or DCs in copper, there is formation of planar array of dislocations and twins on {111} slip plane of austenite phase [18]. Increase in strain results in interaction of twins which leads to further division of the austenite grains into refined blocks. Formation of martensite phase is observed at interactions of twins. For HCP and FCC metals [20, 21] with low stacking fault energy, high density parallel twins are formed to divide the coarse grain into lamellar twin/matrix alternate blocks. On increasing strain twin–twin interactions lead to division of the grain into rhombic blocks and result into nanometer sized crystallites with large angle boundaries.

4 Effect of Nanostructure on Mechanical Properties

Most of the engineering failures like those from fatigue, fretting fatigue, wear and corrosion originate from the surface. Refinement in surface microstructure may

effectively enhance the overall performance and service life of structural components. In the following sections, the effect of surface modification through USSP, on tensile and fatigue behavior of different metals and alloys is presented.

4.1 Tensile Behavior

Surface grain refinement has been observed to enhance tensile properties of metals and alloys [23–26]. Effect of USSP was studied on tensile properties of the superalloy IN718 [27]. TEM micrograph of the un-shot peened sample showed austenite matrix with ordered γ' precipitates and rod like δ phase preferentially at grain boundaries (Fig. 2a). TEM study of the 90 min USSPed sample revealed nanostructure of 12 nm grain size and shear bands with twins. Formation of micro twins was observed following USSP treatment and was confirmed from the elongated diffraction spots (Fig. 2d). Figure 3 shows engineering stress–strain curves of the un-shot peened and USSPed IN718. Yield and tensile strengths may be seen to increase by 3.5 and 2.15 %, respectively and the ductility

to reduce by 3.4 %, following USSP. The cylindrical specimen of 4.5 mm diameter, may be considered of composite nature, following USSP having a thin peripheral region of strong nanostructure. Only the marginal increase in strength parameters may be attributed to very small (5 %) volume fraction of the nanostructure.

Similar effect of the USSP was observed on the tensile behavior of the age hardening aluminium alloy 2014 [28] and the high nitrogen stainless steel [29]. In both the cases considerable improvement was observed in yield and tensile strength and fall in ductility from USSP. The specimen was used with a gage diameter of 4.5 mm, volume fraction of approximately 5 % was affected from USSP therefore the increment in tensile properties was marginal. The strength parameters increase with volume fraction of nanostructure in surface region [30]. An increase of about six times was observed in fully nano structured 316L stainless steel in respect of the coarse grained counterpart [31]. The sample of cross-sectional area of 2 mm × 0.015 mm was subjected to SMAT and the total volume of the specimen was transformed into nano

Fig. 2 Bright field TEM micrographs and corresponding SAD patterns of the samples: **a** un-shot peened **c** 90 min USSPed
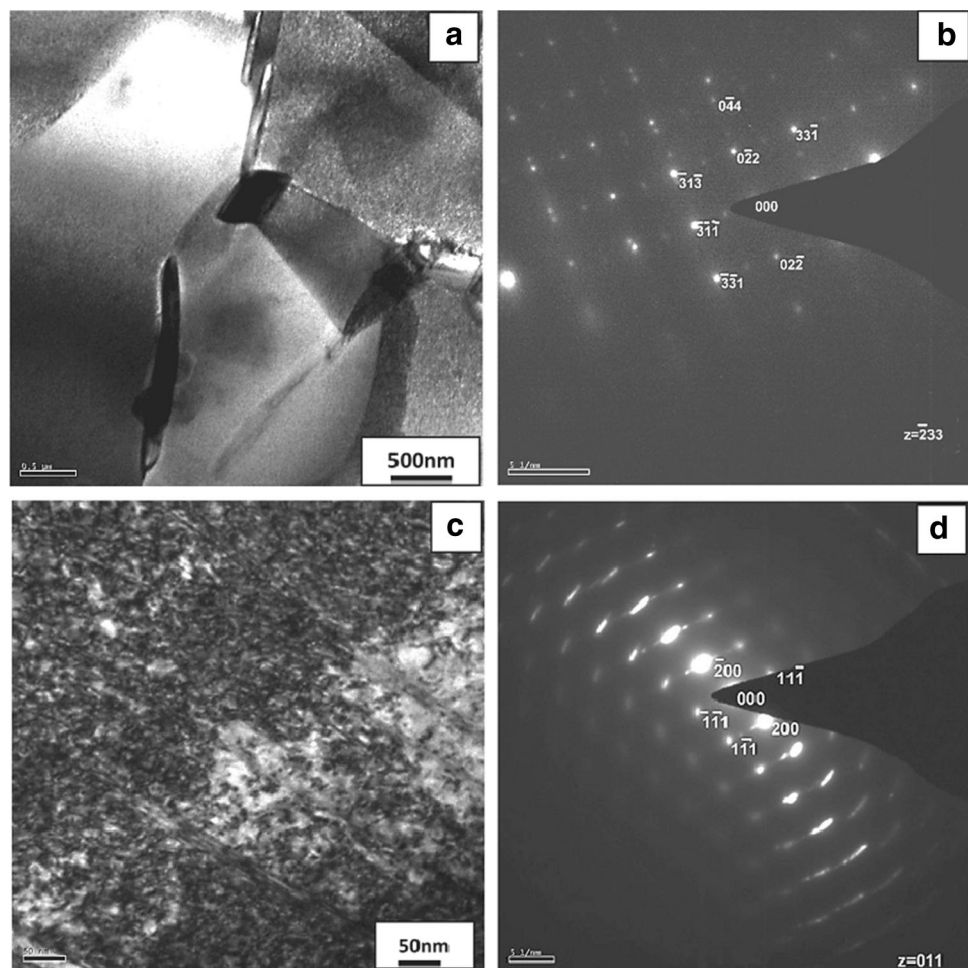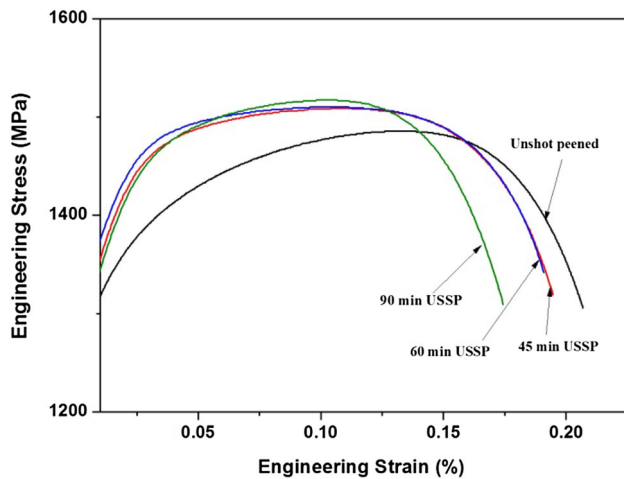
Fig. 3 Tensile engineering stress–strain curves of the un-shot peened and USSP treated IN718 [27]

Fig. 4 Variation of micro hardness with depth, from surface in AA2014 [28]

structure, which led to such increase in strength properties. The fall in ductility due to surface nano structuring (Fig. 3) may be due to increase in surface roughness and tendency for cracking. Tensile behavior of the USSPed samples with increasing duration of shot peening may be seen to be similar to those of cold worked samples with increasing degree of cold working, exhibiting much lower degree of work hardening and decrease in ductility.

4.2 Fatigue

Fatigue is one of the largest factors of failure of structural components and it comprises about 90 % of all the metallic failures. Material with fine grain/nano structured surface layer and coarse grain interior is found to possess high resistance against fatigue failure. A nano structured surface layer retards the process of fatigue crack initiation, whereas a coarse grain interior lowers the rate of fatigue crack growth [32–34]. Moreover, the compressive residual stresses imparted to the component from ultrasonic shot peening also add to retardation of the process of initiation and propagation of fatigue crack [14, 18, 20].

Effect of USSP was studied on LCF behavior of the aluminium alloy 2014 in peak aged condition, using cylindrical specimen of gage diameter 5.5 mm, gage length 15 mm, shoulder radii of 25 mm and threaded ends of 30 mm length and 12 mm diameter [28]. A gradient microstructure was developed from surface towards interior due to variation in strains induced by USSP treatment. With increase in depth from the treated surface, the size of refined grains gradually increased from nanometer to micrometer scale from surface towards the interior. The variation of micro hardness along the cross section, from the treated surface to coarse grained matrix, is shown in Fig. 4. It may be seen that the micro hardness gradually
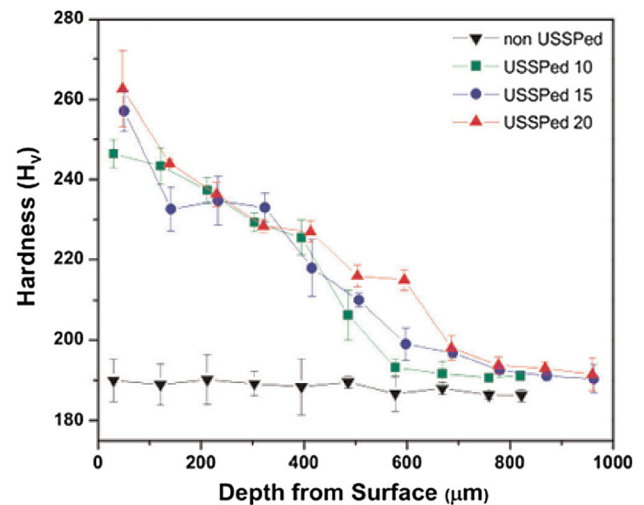
decreased with increase in distance from the surface with progressive increase in grain size, in accordance with Hall–Petch relationship. Partially, it may also be due to higher degree of cold working with increase in duration of USSP.

The bright field TEM micrograph of the AA2014 in Fig. 5a shows microstructure in the un-USSP condition, consisting of fine needle like precipitates (θ') along with coarse spherical (θ) particles. Following the USSP treatment there was formation of nano structure with random crystallographic orientations (Fig. 5c). The corresponding diffraction patterns are shown in Fig. 5b, d respectively.

LCF life was significantly improved due to USSP and there was further improvement from stress relieving treatment and this progressively increased with decrease in strain amplitude. The variation of residual stress in USSPed and stress relieved (USSPed + SR) condition is shown in Fig. 6. Tensile residual stresses generated by the USSP treatment were completely relieved following the stress relieving treatment and there were only compressive stresses even at the greater depth which retarded the rate of crack growth and enhanced the fatigue life. Percent improvement in fatigue life increased as it approached close to the regime of high cycle fatigue. High cycle fatigue tests under stress control mode in the different conditions showed similar trend as that observed in strain controlled low cycle fatigue at the lower strain amplitude. The surface grain refinement resulting from USSP would be more effective at lower strain amplitude in delaying the crack initiation because of activation of only a few favorable slip systems and involving less volume fraction of material in contrast to that at high strain amplitude with activation of large number of slip systems and involving larger volume fraction, in particular materials with low stacking fault energy deforming by planar slip.

Fig. 5 Bright field TEM micrographs and corresponding SAD patterns of the AA201: **a**, **c** un-shot peened, **c**, **d** 10 min USSP treated [28]
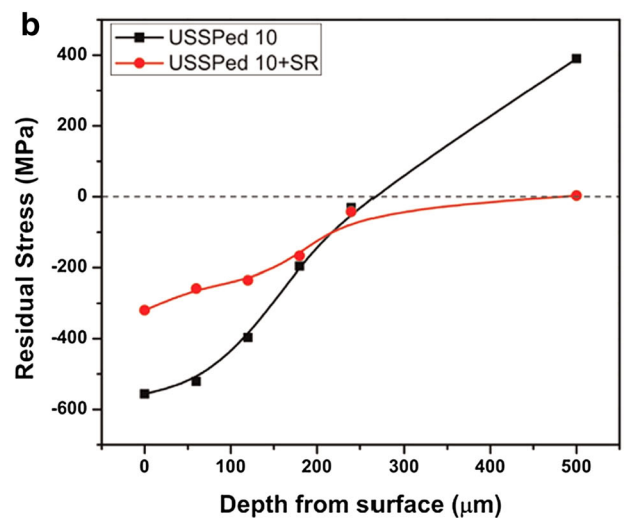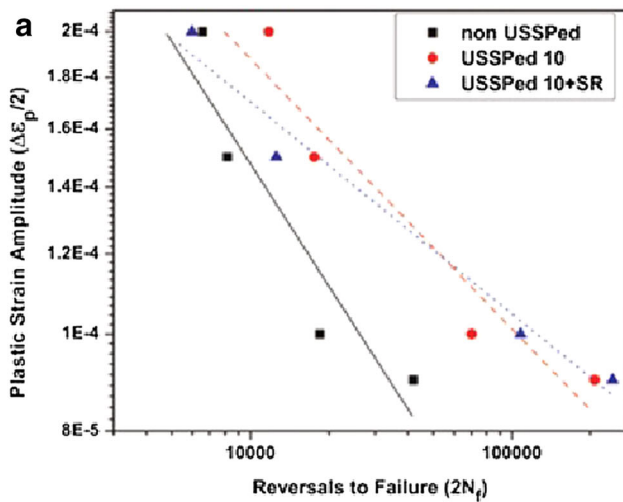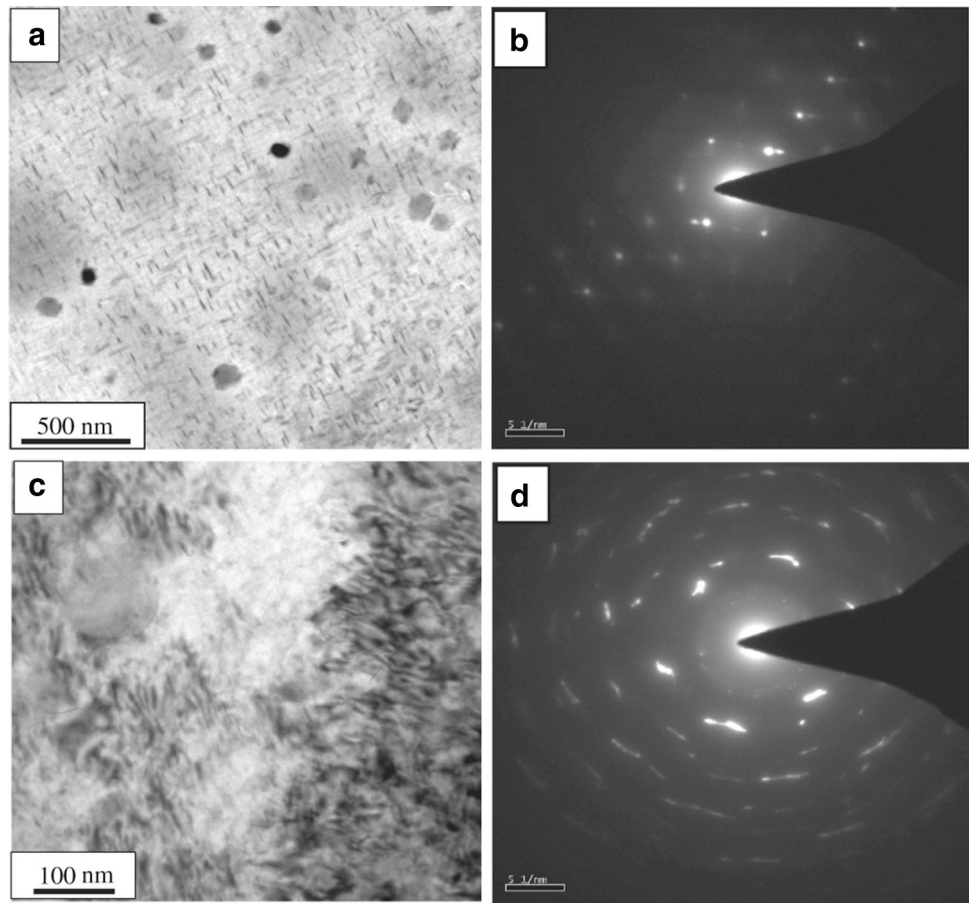

Fig. 6 **a** Variation of fatigue life of AA2014 with plastic strain amplitude, **b** residual stress along the depth of specimen for the USSPed and USSPed 10 + SR conditions [28]

Fractographs revealed that the number of crack initiation sites, shown by white arrows, was more in the USSP treated samples than that in the un-USSPed one (Fig. 7). In case of USSP treated specimens fatigue cracks were non-propagating in nature due to associated high compressive residual stresses, instead there was subsurface fatigue crack initiation in the USSPed 10 and USSPed 10 + SR conditions, as shown by arrows inside
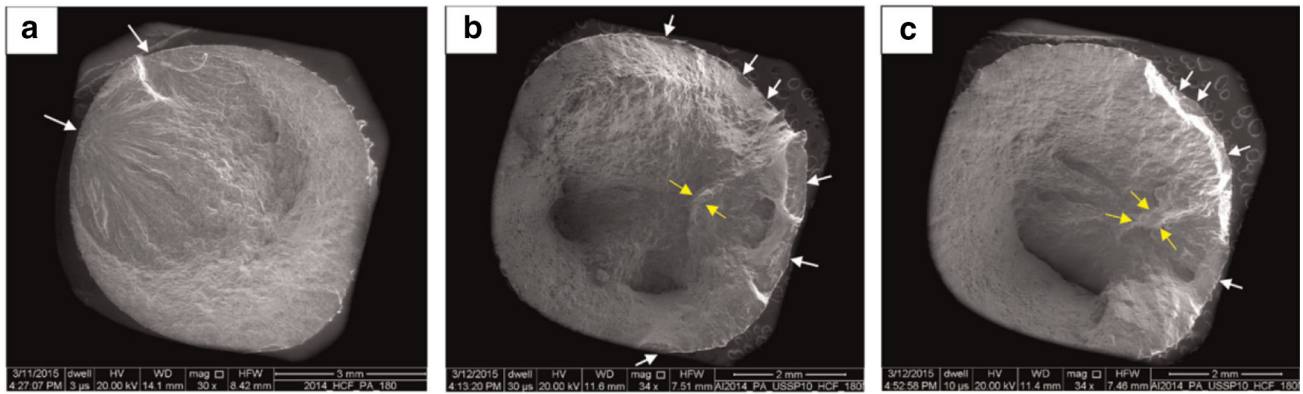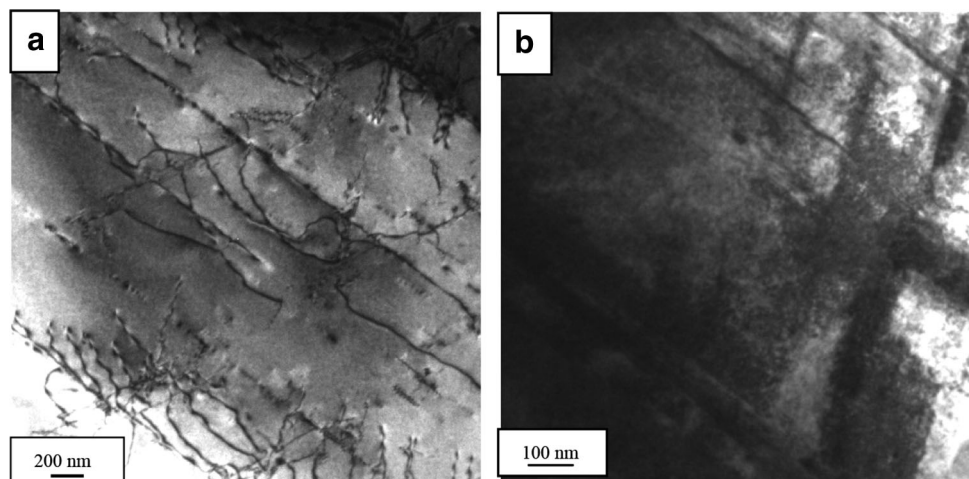
Fig. 7 Fracture surface of the fatigue specimens tested in high cycle fatigue: **a** un-USSPed, **b** USSPed 10, and **c** USSPed 10 + SR [28]

Fig. 8 Bright field TEM micrographs of high nitrogen austenitic stainless steel of the samples: **a** un-shot peened, and **b** 10 min USSP treated [29]

the fracture surface (below periphery) in (Fig. 7 b and c).

Rai et al. [29] examined the effect of USSP on fatigue behavior of high nitrogen austenitic stainless steel under total strain control using cylindrical specimens of the geometry identical to that for the aluminium alloy 2014 given above. Bright field TEM image of the un-shot peened specimen revealed low density of dislocations (Fig. 8a) whereas the USSP treated sample showed extensive intersection of planar slip bands.

At the high strain amplitudes of ±0.73 %, LCF life of the USSP treated specimens was comparable to that of the un-shot peened specimen (Fig. 9) but drastically decreased with decrease in strain amplitude, due to formation of subsurface cracks in the USSPed samples (Fig. 10).

There was also formation of surface cracks, which increased the average surface roughness and reduced the beneficial effect of compressive residual stresses to result in reduced LCF life.
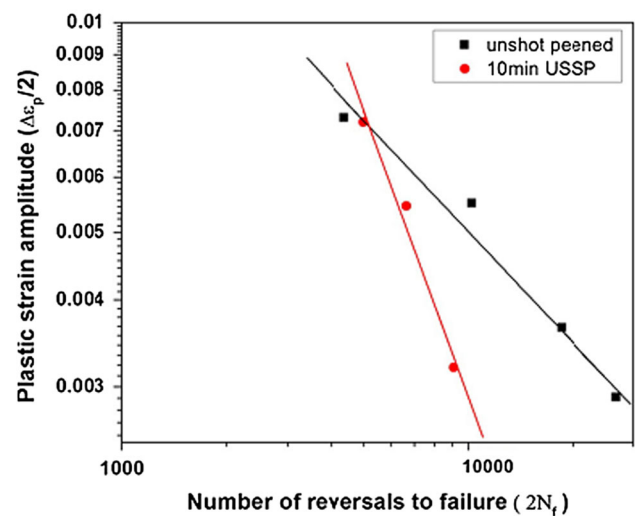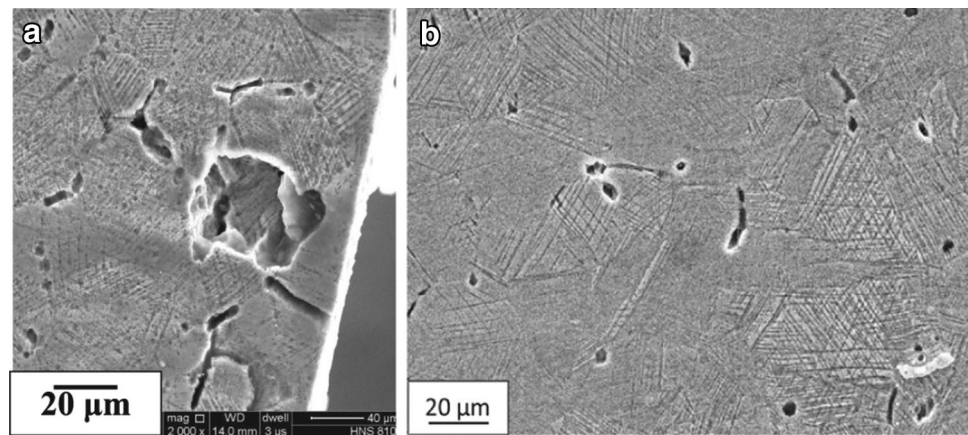

Fig. 9 Coffin–Manson plot for un-shot peened and 10 min shot peened specimens of high nitrogen austenitic stainless steel [29]

Fig. 10 SEM micrograph of high nitrogen austenitic stainless steel showing cracks: **a** at the edge of the specimen shot peened for 13.5 min, **b** sub surface cracks in the specimen USSPed for 10 min [29]

5 Summary

The gradient structure with nanosize surface grains, synthesized by Ultrasonic Shot Peening, causes marked improvement in fatigue resistance of metallic materials without any change in their chemical composition. It is obvious that marked improvement in high cycle fatigue results essentially from refinement of surface grains and delay in the process of crack initiation. However, excessive ultrasonic shot peening leads to surface cracking and impairs fatigue life. Thus, it is essential to optimize surface ultrasonic shot peening for maximum improvement in fatigue resistance.

References

1. Tao N R, Sui M L, Lu J, and K Lu, *Nanostruct Mater* **11** (1999) 433.
2. Liu G, Lu J, and Lu K, *Mater Sci Eng A* **286** (2000) 91.
3. Liu G, Wang S C, Lou X F, Lu J, and Lu K, *Scripta Mater* **44** (2001) 1791.
4. Wu X, Tao N, Hong Y, Xu B, Lu J, and Lu K, *Acta Mater* **50** (2002) 2075.
5. Lu K, and Lu J, *Mater Sci Eng A* **375** (2004) 38.
6. Nalla R K, Altenberger I, Noster U, Liu G Y, Scholtes B, and Ritchie R O, *Mater Sci Eng A* **355** (2003), 216.
7. Clauer A H, *Laser Shock Peening for Fatigue Resistance*, Surface Performance of Titanium, Warrendale (1996), p 217.
8. Janosch J J, Koneczny H, Debiez S, Statnikov E C, Troufiakov V J, and Mikhee P P, *Improvement of Fatigue Strength in Welded Joints (in HSS and in Aluminium Alloys) By Ultrasonic Hammer Peening*, Welding in The World, London (1996), p 72.
9. Jian L, *J Mater Sci Technol* **15** (1999) 193.
10. Sonsino C M, Mueller F, and Mueller R, *Int J Fatigue* **14** (1992) 3.
11. Umemoto M, Todaka K, and Tsuchiya K, *Mater Sci Eng A* **375–377** (2004), 899.
12. Umemoto M, *Mater Trans* **44** (2003) 1900.
13. Li J G, Umemoto M, Todaka Y, and Tsuchiya K, *Mater Sci Eng A* **435–436** (2006) 383.
14. Lu K, and Lu J, *Mater Sci Eng A* **375–377** (2004) 38.
15. Liu G, Lu J, and Lu K, *Mater Sci Eng A* **286** (2000) 91.
16. Wu X, Tao N, Hong Y, Xu B, Lu J, and Lu K, *Acta Mater* **50** (2002) 2075.
17. Tao N R, Wang Z B, Tong W P, Lu J, and Lu K, *Acta Mater* **50** (2002) 4603.
18. Zhang H W, Hei Z K, Liu G, Lu J, and Lu K, *Acta Mater* **51** (2003) 1871.
19. Wang K, Tao N R, Liu G, Lu J, and Lu K, *Acta Mater* **54** (2006) 5281.
20. Zhu K Y, Vassel A, Brisset F, Lu K, and Lu J, *Acta Mater* **52** (2004) 4101.
21. Wu X, Tao N, Hong Y, Liu G, Xu B, Lu J, and Lu K, *Acta Mater* **53** (2005) 681.
22. Sun H Q, Shi Y N, Zhang M X, and Lu K, *Acta Mater* **55** (2007) 975.
23. Chattopadhyay K, Pandey V, Srinivas N C S, and Singh V, *IOP Conf Ser Mater Sci Eng* **63** (2014) 012017.
24. Li J, Chen S, Wu X, Soh A, and Lu J, *Mater Sci Eng A* **527** (2010) 7040.
25. Cai B, Ma X, Moering J, Zhou H, Yang X, and Zhu X, *Mater Sci Eng A* **626** (2015) 144.
26. Yang X, Ma X, Moering J, Zhou H, Wang W, Gong Y, and Zhu X, *Mater Sci Eng A* **645** (2015) 280.
27. Kumar S, Rao G S, Chattopadhyay K, Mahobia G S, Srinivas N C S, and Singh V, *Mater Design* **62** (2014) 76.
28. Pandey V, Rao G S, Chattopadhyay K, Srinivas N C S, and Singh V, *Mater Sci Eng A* **647** (2015) 201.
29. Rai P K, Pandey V, Chattopadhyay K, Singhal L K, and Singh V, *J Mater Eng Perf* **23** (2014) 4055.
30. Wu X L, Jiang P, Chen L, Zhang J F, Yuan F P, and Zhu Y T, *Mater Res Lett* **2** (2014) 185.
31. Chen X H, Lu J, Lu L, and Lu K, *Scr Mater* **52** (2005) 1039.
32. Suresh S, *Fatigue of Materials*, Cambridge University Press, New York (1991).
33. Hanlon T, Kwon Y N, and Suresh S, *Scr Mater* **49** (2003) 675.
34. Mughrabi H, Hoppel H W and Kautz M, *Scr Mater* **51** (2004) 807.