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ÜBERSICHTSARBEITEN/REVIEW ARTICLES

Current research status of influence of ball burnishing process on fatigue behavior: a review

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Abstract
The importance of surface integrity to fatigue behavior was reviewed. Firstly, the classification, working principle and strengthening characteristics of the ball burnishing process were introduced in detail. Subsequently, the effects of process parameters on the surface integrity and surface integrity on the fatigue behavior are summarized. It can be seen from the research results that the surface roughness decreased rapidly, and then the surface micro-hardness and surface residual compressive stress increased significantly as well as the fatigue behavior could be improved effectively after the ball burnishing process. In addition, the surface microstructure also changed enormously and the gradient nanostructured surface (GNS) layer could be prepared by special ball burnishing parameters. Finally, some suggestions were put forward for the problems existing in the preparation process of the GNS surface layer, which provided some ideas for the further research of anti-fatigue manufacturing technology.

Aktueller Forschungsstand zum Einfluss des Oberflächenwalzverfahrens auf das Ermüdungsverhalten: Ein Überblick

Zusammenfassung
Die Bedeutung der Oberflächenintegrität für die Ermüdungsverhalten wurde untersucht. Zunächst wurden die Klassifizierung, das Arbeitsprinzip und die Verfestigungseigenschaften des Kugelpolierverfahrens im Detail vorgestellt. Anschließend werden die Auswirkungen der Prozessparameter auf die Oberflächenintegrität und die Oberflächenintegrität auf das Ermüdungsverhalten zusammengefasst. Aus den Forschungsergebnissen geht hervor, dass die Oberflächenrauheit rasch abnahm, die Mikrohärte der Oberfläche und die Oberflächendruckeigenspannung deutlich zunahmen und das Ermüdungsverhalten nach dem Kugelpolierverfahren wirksam verbessert werden konnte. Darüber hinaus änderte sich auch die Oberflächenmikrostruktur enorm, und die Schicht mit der Gradienten-Nanostruktur (GNS) konnte durch spezielle Kugelpolierparameter hergestellt werden. Abschließend wurden einige Vorschläge für die Probleme bei der Herstellung der GNS-Oberflächenschicht unterbreitet, die einige Ideen für die weitere Erforschung der Anti-Ermüdungs-Fertigungstechnologie lieferten.

1 Introduction

As the key component of the aero-engine, the service reliability of the blade has an important influence on the comprehensive behavior and flight safety of the aero-engine. At present, the aero-engine blade has been improved greatly in terms of structural design and service life [1, 2]. However, fatigue failure of the blade is inevitable under the action of alternating loads generated by the engine working cycle. In recent years, with the continuous improvement of aero-engine speed and pressure ratio, the operating environment of the blade has become increasingly harsh, and its service life and reliability have become important factors affecting the flight safety of civil aviation aircraft.

According to statistics, 80% of failure modes of aero-engine blades were fatigue failure, and fatigue crack sources of parts occurred generally on the surface [3–8]. This phe-

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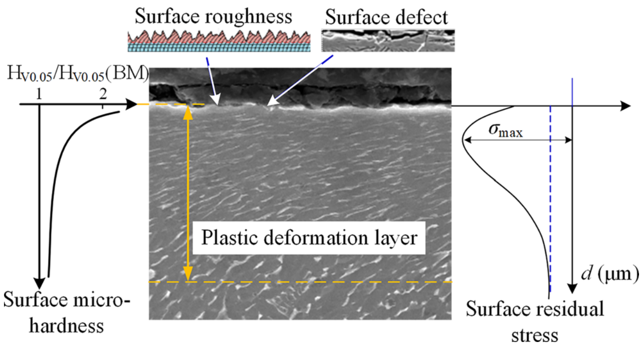


Fig. 1 Key indicators of machined surface integrity

nomenon showed that the fatigue life of the part could be affected directly by the surface quality. The factors affecting the surface quality are referred collectively to as surface integrity, mainly including surface roughness, surface micro-hardness, surface residual stress and surface microstructure. The concept of surface integrity was proposed by Field and Kahles [9] in 1964, which referred to the physical and chemical properties of the part surface produced under processing conditions, including the microscopic geometric and material microstructure characteristics of the processed surface, as shown in Fig. 1.

To improve the surface integrity and fatigue behavior of the part, a ball burnishing process was developed by researchers. The process involves applying a certain amount of force to the surface of the sample using a burnishing tool, which causes the material on the surface of the sample to undergo plastic flow and work-hardening, thereby reducing the surface roughness, decreasing surface defects, increasing the surface micro-hardness and introducing the surface residual compressive stress, and thus improving the fatigue resistance. In addition, due to the characteristics of no chips, no pollution, and good compatibility in the process, the ball burnishing process is widely used in the finishing of machining.

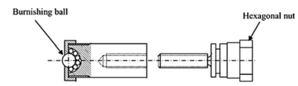
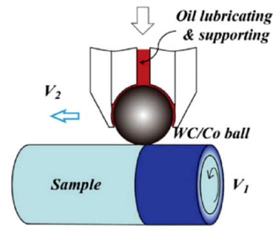
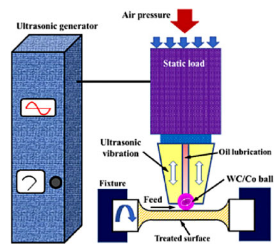
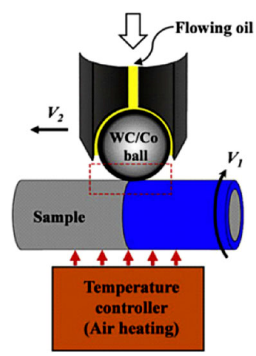
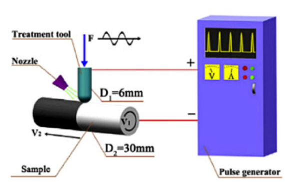
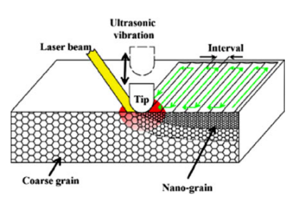
2 Classification and strengthening mechanism of the ball burnishing process

The traditional burnishing process appeared in Germany in 1929 [10]. Subsequently, in order to improve the strengthening effect, the ball burnishing process was developed, such as center rest ball burnishing (CRBB) process, low-plasticity ball burnishing (LPBB) process, ultrasonic-assisted ball burnishing process (UABB), high-temperature ball burnishing (HTBB) process, electropulsing-assisted ball burnishing (EABB) process and laser-assisted ball burnishing (LABB) process, as shown in Table 1.

The free rotation of the burnishing tool in the CRBB process was achieved by the rolling contact between the burnishing tool and some small balls [11]. The LPBB process was developed by the University of Kassel in Germany [12]. The working principle was to press the free burnishing tool on the surface of the part through hydraulic pressure, so as to reduce the surface roughness and introduce the residual compressive stress [13, 14]. However, the thin-walled part wasn't suitable for being strengthened by the LPBB process because the burnishing force was too high. To decrease the burnishing force, the UABB process was developed, which can not only introduce higher residual compressive stress but also has a small burnishing force [15]. In addition, the HTBB process was also developed, which required the temperature of the material to be higher than room temperature during ball burnishing, so as to obtain the surface microstructure with finer grains [16, 17]. In order to achieve a better strengthening effect, many special processes have also been tried by researchers, such as the EABB process, LABB process, and so on [18, 19].

The burnishing velocity, burnishing force, feed rate and diameter of burnishing tool were included mainly in the ball burnishing process parameters, as well as additional parameters such as the number of burnishing passes, the amplitude of ultrasonic vibration, processing temperature, current density and the types of the working scheme (one-way or two-way) [13–19]. The strengthening effect of the material surface was related closely to the selection of parameters. In general, the smaller the feed rate, the smaller the surface roughness. The larger the burnishing force or the more burnishing passes, the greater the dislocation density, grain refinement, micro-hardness and residual compressive stress on the surface of the material. As far as the strengthening effect was concerned, the fatigue life of ball burnishing samples was significantly higher than that of the untreated sample. The main reasons generally included three aspects. Firstly, the ball burnishing process caused a plastic flow of the material on the surface, which produced a peak-cutting and valley-filling effect [20], thus smoothing the surface and eliminating stress concentrations. Secondly, the localized plastic deformation caused by ball burnishing process introduced residual compressive stresses on the surface of the material, which delayed the rate of crack propagation [21–25]. In addition, the cyclic plastic deformation of the surface material could be induced by ball burnishing process, which promotes grain refinement, dislocation density, interplanar spacing and surface micro-hardness [26–30]. Moreover, when a fatigue crack traverses a dislocation wall formed by a significant accumulation of dislocations, it necessitates overcoming additional energy dissipation, resulting in a decelerated rate of crack growth and an extended fatigue life of the sample [31].

Table 1 Schematic illustration of ball burnishing processes

Process	Schematic illustration	Ref
Center rest ball burnishing (CRBB)		[11]
Low-plasticity ball burnishing (LPBB)		[63]
Ultrasonic-assisted ball burnishing process (UABB)		[57]
High-temperature ball burnishing (HTBB)		[78]
Electropulsing-assisted ball burnishing (EABB)		[18]
Laser-assisted ball burnishing (LABB)		[19]

3 The influence of ball burnishing parameters on the surface integrity

3.1 Surface roughness

The small spacing and the unevenness on the machined surface are called surface roughness. The surface roughness was the main factor that induced the fatigue crack on the surface of the part. Groove marks on the rough surface could cause stress concentration, induce crack initiation, and decrease the fatigue life of the material [32]. In addition, the higher surface roughness was often accompanied by deeper surface scratches and other machining defects, reducing the fatigue resistance of part. Meanwhile, surface roughness was also considered to be one of the most important indicators of surface integrity [33].

Generally, the ball burnishing process could reduce effectively the surface roughness of the part [34]. For exam-

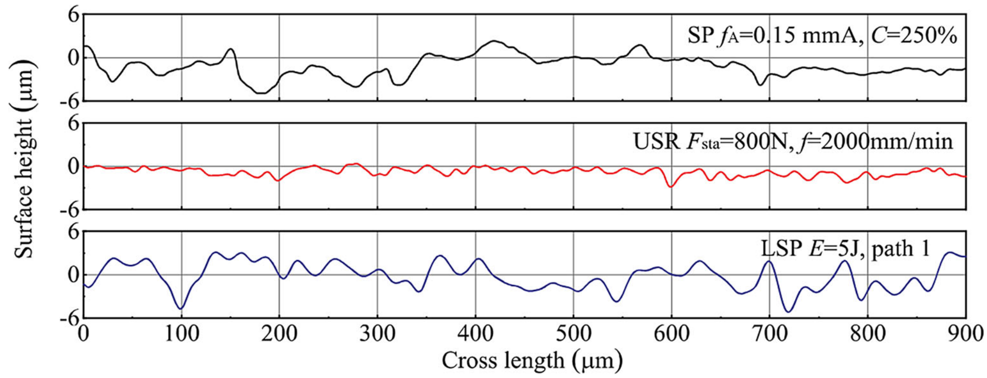


Fig. 2 Surface profile height comparison under different surface treatment processes [36]

ple, The effect of LPBB process on the surface quality of X38CrMoV5-1 steel was studied by Swirad et al. [35]. They found that the surface profile was smoother and the surface roughness also decreased significantly in comparison to the grinding process. Similarly, Yao et al. [36] explored the influence of different surface strengthening processes on the surface integrity of TC17 titanium alloy. The results showed that the USR (i.e. UABB) process could decrease effectively the residual height of the material surface in comparison to shot peening and laser shock shot peening, as shown in Fig. 2.

However, Sánchez et al. [37] treated 2050 aluminum alloy formed by friction stir welding through LPBB process. It was indicated that the surface quality of the burnishing surface was better compared with the original surface, but excessive burnishing force could damage the surface morphology of the part. Consistent conclusions were drawn by Yaser et al. [38], who investigated the effect of parameters on the surface quality of low carbon steel by LPBB process. They found that the trend of surface roughness first decreased and then rose with the increase of burnishing force and feed. In addition, Ren et al. [39] investigated the influence of USR (i.e. UABB) process on the Ti5Al4Mo6V2Nb1Fe titanium alloy, the results showed that the increase of burnishing passes and burnishing force decreased evidently the surface roughness, but excessive passes or burnishing force also increased the surface roughness again, as shown in Fig. 3. The similar phenomenon was observed by Liu et al. [40], who studied the surface conditions of 17-PH steel after UABB process. They believed that the increase of the surface roughness was caused by the delamination of the surface material under excessive plastic deformation. Tayeb et al. [41] investigated the effect of ball diameter on the surface roughness of 6061 aluminum alloy using the LPBB process. The results showed that the surface roughness decreased continuously with the increase in ball diameter. However, when the ball diameter was too large, the surface quality deteriorated. On the one hand, due to the increase in ball diameter, the burnishing force acting on the sample surface was smaller, making the peak-cutting and valley-filling effect worse, resulting in the surface roughness rising again. On the other hand, the contact area between the burnishing tool and the sample surface became larger, which increased the frictional heat and made the surface quality worse.

3.2 Surface micro-hardness

The ability of the material to resist locally the pressing of hard objects into its surface is called micro-hardness. The wear resistance of the part can be improved by increasing the surface micro-hardness. During the ball burnishing process, cyclic plastic deformation occurs in surface material under the action of the burnishing tool, resulting in the in-

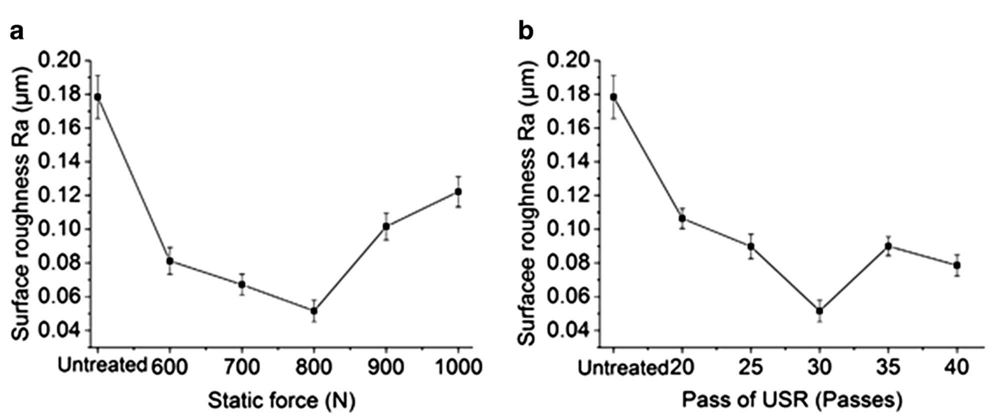


Fig. 3 Influence of parameters on the surface roughness. **a** Burnishing force. **b** Burnishing passes [39]

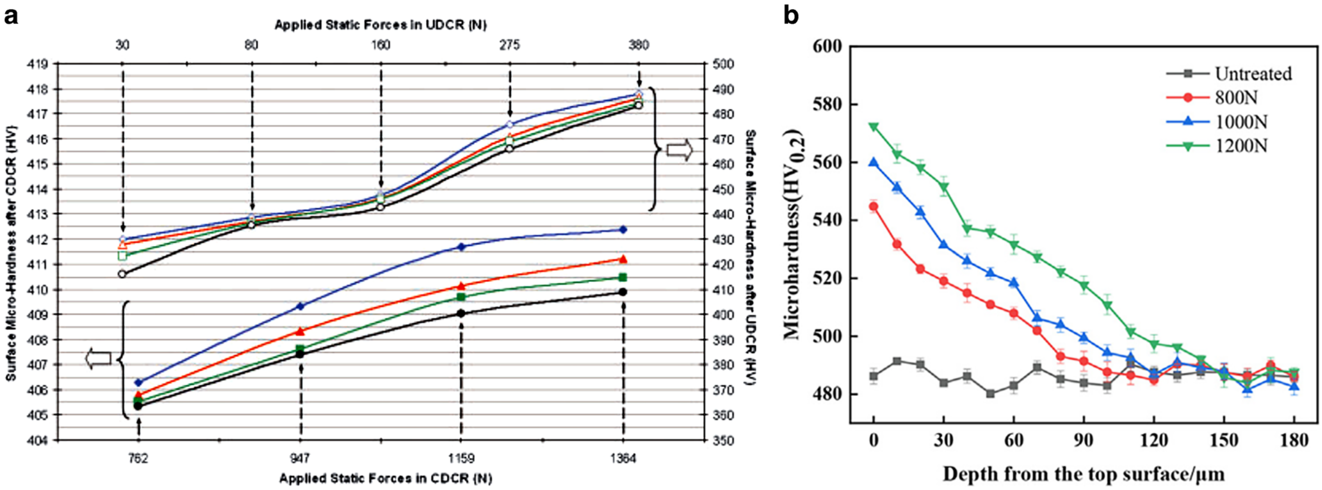


Fig. 4 Surface micro-hardness. **a** CDCR (i.e. LPBB) process and UDCR (i.e. UABB) process [48]. **b** Along depth under different burnishing forces [49]

crease of dislocation density and lattice distortion in the surface microstructure, which in turn leads to work hardening. In addition, when process parameters are changed, the degree of work hardening also varies.

Alberto et al. [42] studied the effect of LPBB process on the surface integrity of AISI 1045 steel. It was found that the increase in burnishing force and feed rate played a positive role in the surface micro-hardness. The effect of the LPBB process on the surface micro-hardness of Al-Cu alloys was studied by Hassan et al.[43]. They found that the surface micro-hardness decreased as the ball diameter increased. They concluded that the larger ball diameter increased the contact area between the burnishing tool and the sample, which reduced the penetration depth of burnishing tool, which in turn reduced the plastic deformation of the sample surface, leading to a decrease in the degree of work-hardening. However, Rao et al. [44] tested the effect of ball diameter (8 mm ~ 20.2 mm) on the surface microhardness of HSLA duplex steels in a ball burnishing process. They found that the surface micro-hardness increased with increasing ball diameter, but when the diameter was too large, the surface layer of the sample flaked off. This phenomenon was investigated further by Attabi et al. [45]. During the study of the effect of the LPBB process on 316L stainless steel, They found that when the burnishing force was at a low or medium level, the effect of ball diameter on surface micro-hardness was not significant, while when the burnishing force was at a high level, the biggest ball (d = 13 mm) had the highest surface micro-hardness. They attributed this to the fact that the plastic deformation caused by the penetration of the greatest ball covered a larger surface, which resulted in more work hardening on the surface, and thus higher values of micro-hardness could be attained.

To further explore the effect of the ball burnishing process on the surface micro-hardness, various auxiliary processes were tried by researchers. The combined turning-burnishing process was used in studying the surface integrity of AISI 4140 steel by Rami et al. [46]. The results showed that the surface micro-hardness could be improved effectively by the combined turning-burnishing process compared with the single turning process, and the most important factor was the diameter of burnishing tool. The same material was studied by Tian et al. [47] through the laser-assisted burnishing process. It could be seen that the softened material surface could aggravate the degree of plastic deformation, resulting in a larger surface micro-hardness. The surface integrity of Ti-6Al-4V titanium alloy through LPBB and UABB process was investigated by Bozdana et al. [48], which found that the surface micro-hardness of the UABB sample was higher than that of the LPBB sample, as shown in Fig. 4a. The UABB process was also used by Zhang et al. [49], which investigated the mechanical properties of 25CrNi2MoV steel. The results in Fig. 4b showed that not only the surface micro-hardness increased, but also the depth of the hardened layer rose with the increase of burnishing force.

3.3 Surface residual stress

The tensile residual stress, as an unstable internal stress, made the parts more prone to cracks and damage when subjected to external forces. However, the surface residual compressive stress could optimize the size and distribution of the surface stress during the service process of the part. In addition, under the same external load and surface roughness conditions, a larger surface residual compressive stress could decrease the strength factor of the fatigue crack tip and delay the fatigue crack propagation, which in turn has a beneficial effect on fatigue life [50].

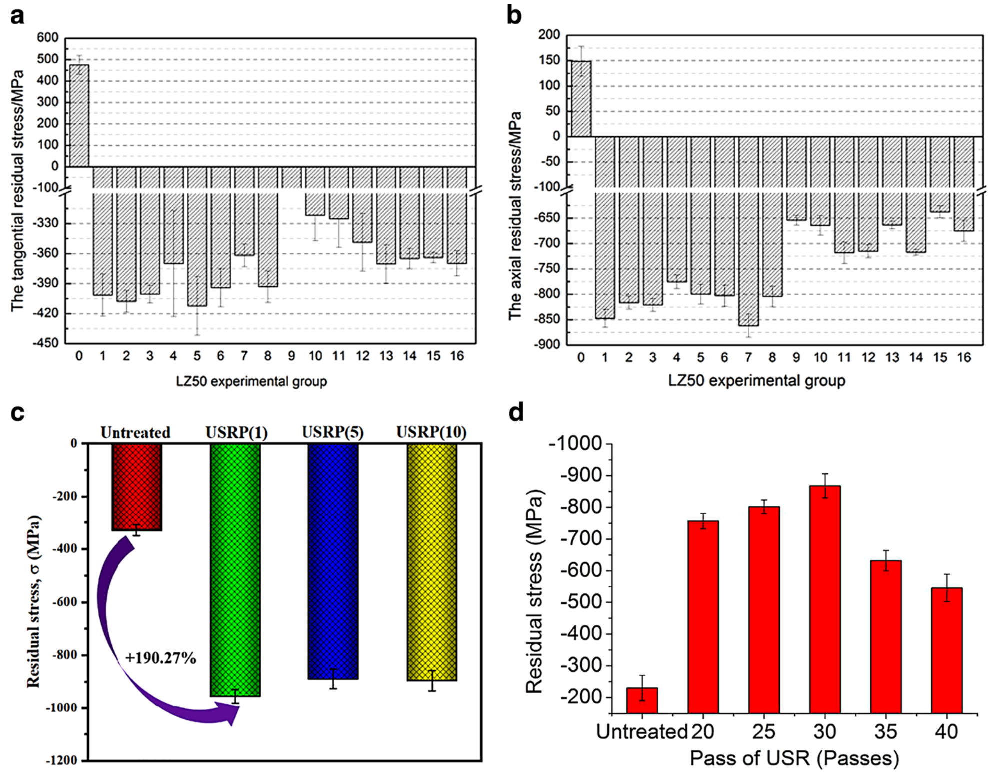


Fig. 5 The effect of parameters on the surface residual stress. **a**,**b** The tangential residual stress and axial residual stress [55]. **c**,**d** Number of passes [40, 57]

Generally, the surface strengthening process can generate residual compressive stress on the surface of the material [51, 52]. Rodríguez et al. [53] conducted the research on AISI 1045 steel by LPBB process. The results showed that the surface residual compressive stress continued to rise with the increase of burnishing force. The influence of parameters on the surface integrity of TA2 titanium alloy was studied by Sun et al. [54], who found that the main factors affecting the surface residual stress were the burnishing force and burnishing passes. The burnishing force and burnishing passes were related positively to the surface residual compressive stress. Fu et al. [55] conducted the surface treatment of LZ50 axle steel by LPBB process through the orthogonal test method. They showed that the tensile residual stress after turning process was transformed into residual compressive stress on the material surface after LPBB process, as shown in Fig. 5a, b. Among them, the axial residual compressive stress was significantly larger than the tangential residual compressive stress. Similar results were drawn by Karthick et al. [56], who studied the additively manufactured GH4169 superalloy by LPBB process. They also found that the burnishing force was the factor that caused the largest change in the residual compressive stress. Dang et al. [57] studied the effect of UABB process on the surface integrity of 300M steel. The results showed that a large surface residual compressive stress could be generated by the USRP (i.e. UABB process). However, the surface residual compressive stress didn't promote significantly with the increase of burnishing passes, as shown in Fig. 5c. The consistent phenomenon was obtained by Liu et al. [40], who also found that the surface residual compressive stress decreased evidently when the number of burnishing passes was too large, as shown in Fig. 5d. They believed that the reason was that too many passes exceeded the critical value that the surface material could withstand. Su et al. [58] researched the surface quality of TC11 titanium alloy through HTBB process. They revealed that the surface residual compressive stress of the HTBB sample was smaller than that of the LPBB sample. The main reason was that the residual compressive stress had a certain degree of release during HTBB process.

3.4 Surface microstructure

During the ball burnishing process, the surface material of the component underwent cyclic plastic deformation, which not only formed a deformed layer of a certain thickness but also the microstructure appeared the phenomenon of grain refinement and increased dislocation density. Zhao et al. [59] studied the surface microstructure of TC4 titanium alloy through the UABB process. They found that the phenomenon of grain refinement occurred on the surface, where the amplitude was the main factor affecting the grain size. When the amplitude of ultrasonic vibration was 7 μm, the surface grain size was the smallest, as shown in Fig. 6. Zhang et al. [60] carried out the surface treatment

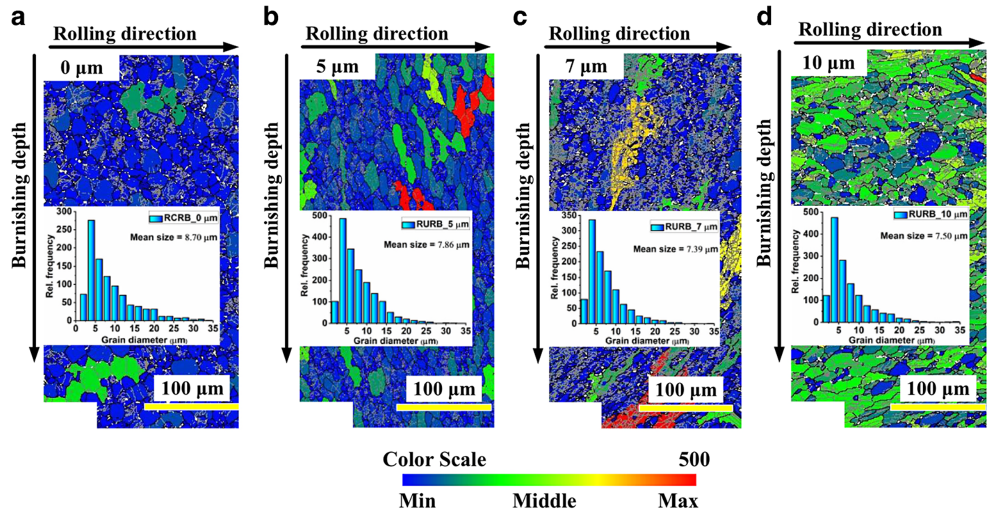


Fig. 6 Surface microstructure at different amplitudes after UABB process [59]

of pure nickel N4 by UABB process. The results showed that under the action of multi-pass burnishing, the surface microstructure could form new grain boundaries and subgrain boundaries due to the continuous movement, proliferation, rearrangement and annihilation of dislocations during cyclic plastic deformation. The ultra-fine grain structure was also produced, with the smallest grain size approaching to 250 nm.

In the process of exploring the influence of surface microstructure on the strength of the sample, the researchers found that the finer the grains, the higher the strength of the sample. When the grain size of the surface material

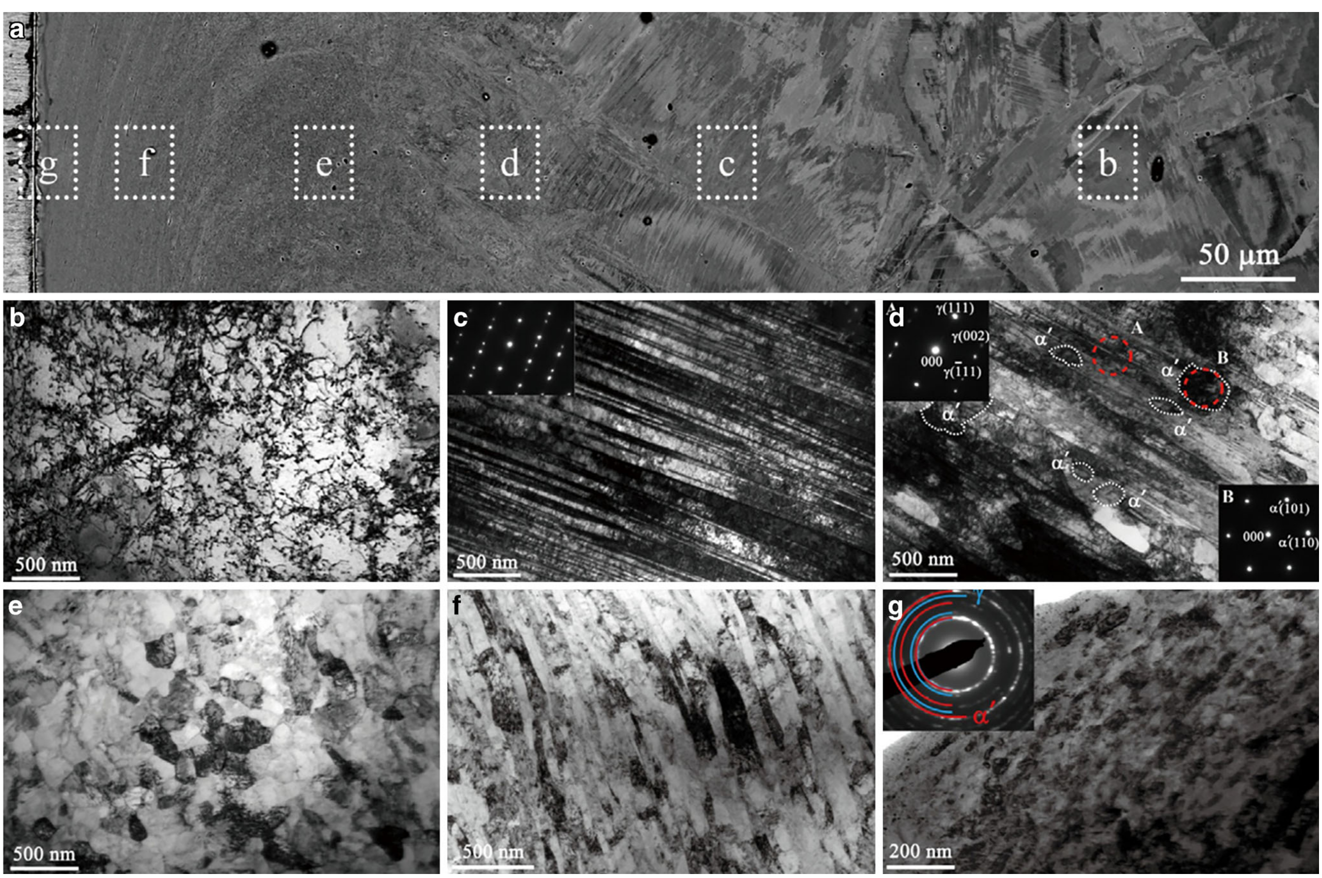


Fig. 7 Microstructure of the GNS surface layer: **a** A typical cross-sectional SEM image of the LPBB sample. **b–g** Bright-field cross-sectional TEM observations at different depths [63]

reached the nanometer level(below 100 nm), the strength of the sample was improved greatly, but its plasticity was decreased significantly [61]. To this end, Lu et al. [62, 63] proposed and prepared the gradient nanostructured (GNS) surface layer, which could not only promote the strength of the sample but also make the sample retain a high degree of plasticity. The microstructure of the GNS surface layer was shown in Fig. 7. However, it was difficult to prepare the GNS surface layer on the metallic material under ordinary process conditions and parameters. Therefore, researchers have made a lot of process improvements and attempts.

Wang et al. [64] prepared the GNS surface layer on 40Cr steel by UABB process. The results showed that the minimum size of the GNS surface layer reached 3 ~ 7 nm, the thickness reached 150 µm, and the wear resistance of the sample was improved evidently. Duan et al. [65] not only prepared the GNS surface layer on X210CrW12 steel by the same process, but also found that the austenite phase on the surface was also transformed into the martensite phase. Sun et al. [66] prepared the GNS surface layer on the Zircaloy-4 alloy by LPBB process and explored the grain growth conditions at different annealing temperatures. It was found that the grain size had almost no significant change at the annealing temperature of 400 °C, while the grain size increased rapidly to the micron level at the annealing temperature of 600 °C.

According to the research of many scholars, it could be found that the number of burnishing passes was the main factor affecting the transformation of the surface microstructure. The depth of the deformed layer and the degree of grain refinement kept rising with the increase of burnishing passes, but excessive burnishing passes also caused the surface of the material to be broken.

4 The effect of surface integrity on fatigue behavior by ball burnishing process

The research of the effect of ball burnishing process on the fatigue behavior of the sample was based on the influence of parameters and conditions on the surface integrity. To explore the fundamental reason why the ball burnishing process improved the fatigue behavior of the sample, many scholars have analyzed deeply the relationship between the fatigue behavior of the sample and surface integrity indexes.

4.1 The effect of surface roughness on fatigue behavior

Decreasing surface roughness generally relieves stress concentrations, which in turn enhanced the fatigue life of the sample [67]. However, when the ball burnishing process parameters are too large or too small, it also leads to a sharp increase in surface roughness. For this reason, scholars have comparatively studied the effect of surface roughness produced by different parameters on fatigue behavior.

Liu et al.[40] conducted the effect of different passes (1 pass, 3 passes and 6 passes) on the fatigue behavior of 17-4PH steel by the UABB process. The results showed that the fatigue life increased and then decreased with the increase of burnishing passes, and fatigue life is highest when the number of burnishing passes was 3 passes, as shown in Fig. 8a. To analyze this result, fatigue fracture was observed in Fig. 9. They found that the fatigue crack sources of the untreated and the UABB-1(1 pass of UABB) samples all appeared on the surface, while the fatigue crack sources of the UABB-3(3 passes of UABB) and UABB-6 (6 passes of UABB) samples appeared on the subsurface. This indicated that the increase in burnishing passes has a positive effect on inhibiting the fatigue crack initiation. However, the fatigue life of the UABB-6 sample was lower than that of the UABB-3 sample, and the location of the fatigue crack source of the UABB-6 sample was also closer to the surface than that of the UABB-3 sample. They concluded that too many burnishing passes led to a rapid increase in surface roughness, which in turn caused shallow crack initiation and a decrease in the fatigue life of sample. Yang et al. [68] obtained similar conclusions when they investigated the effect of burnishing passes (1 pass and 24 passes) on the fatigue behavior of GH4169 alloy by

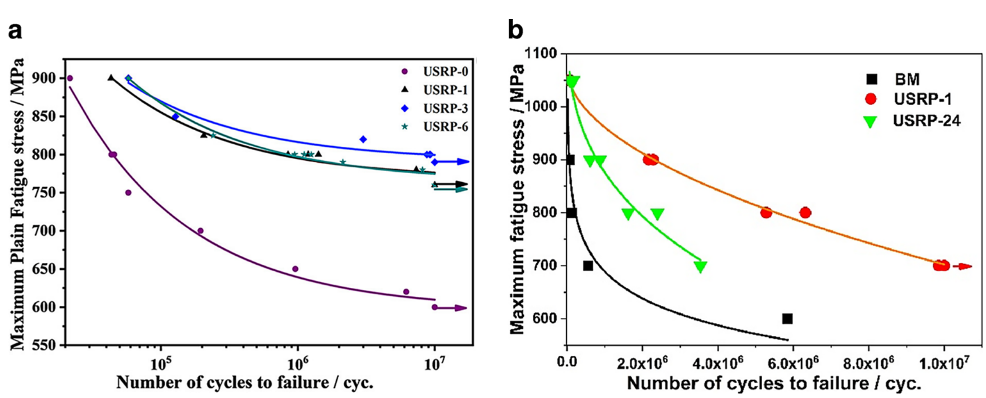


Fig. 8 S/N S/N curves. **a** USRP-0 (i.e. untreated) sample, USRP-1 (i.e. 1 pass of UABB) sample, USRP-3 (i.e. 3 passes of UABB) sample, USRP-6 (i.e. 6 passes of UABB) sample [40]; **b** BM (i.e. untreated) sample, USRP-1 (i.e. 1 pass of UABB) sample, USRP-24 (i.e. 24 passes of UABB) sample [68]

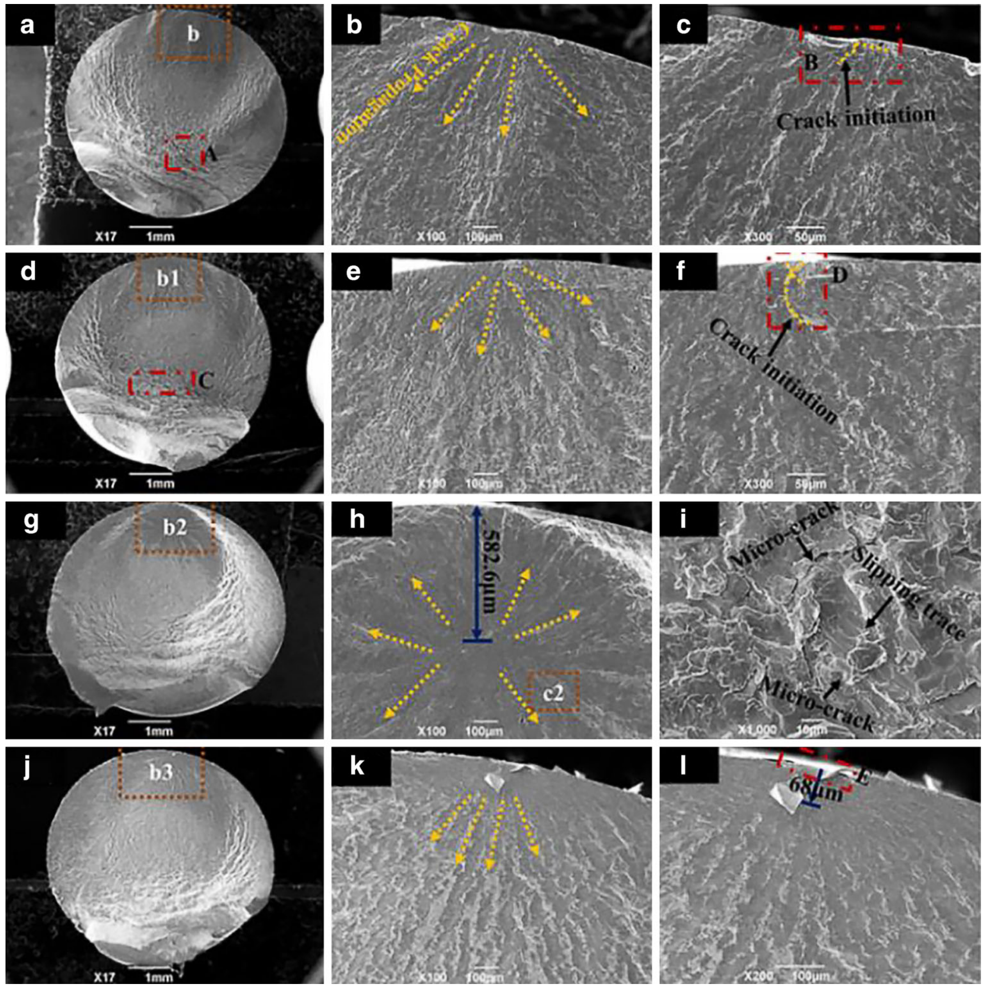


Fig. 9 Fatigue fracture. (**a–c**) USRP-0 (i.e. untreated) sample; **d–f** USRP-1 (i.e. 1 pass of UABB) sample; **g–i** USRP-3 (i.e. 3 passes of UABB) sample; **j–l** USRP-6 (i.e. 6 passes of UABB) sample [40]

the UABB process. They found that although the UABB-24 sample had higher surface micro-hardness and surface residual compressive stresses, the fatigue life of the UABB-24 sample was lower than that of the UABB-1 sample, as shown in Fig. 8b. They conducted that the key factor was due to the UABB-1 sample having lower surface roughness than the UABB-24 sample. By observing the fatigue fracture(Fig. 10), they also found multiple microcrack initiation points on the surface of the UABB-24 sample. This result also proved the importance of surface roughness effect on fatigue behavior in ball burnishing process.

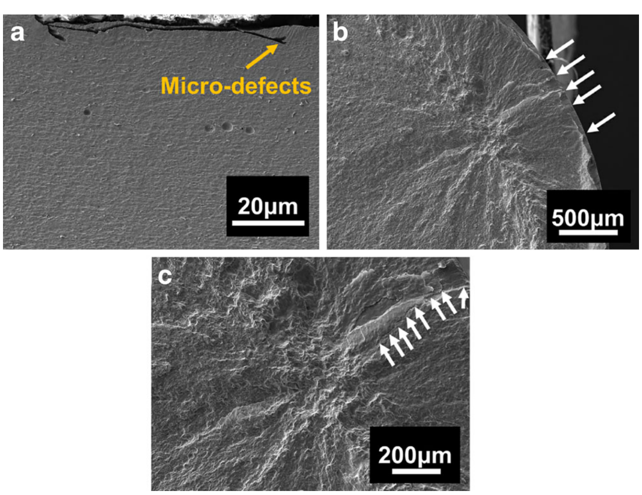


Fig. 10 Fatigue fracture and surface micro-defects of USRP-24 (i.e. 24 passes of UABB) sample [68]. **a** Micro-defects in the top surface; **b** Fatigue crack initiation; **c** Fatigue crack propagation

4.2 The effect of surface micro-hardness on fatigue behavior

The surface micro-hardness increased by the ball burnishing process usually has a positive impact on the fatigue life of the sample [17]. Especially in certain fatigue tests, the surface micro-hardness is extremely critical in improving fatigue life. For example, Zhao et al. [34] applied the UABB process on the fretting fatigue life of 300M steel. The results showed that the fretting fatigue life of burnished samples was significantly improved. By observing fatigue fracture (Fig. 11), they concluded that the main reason was that the high micro-hardness of the UABB sample slowed

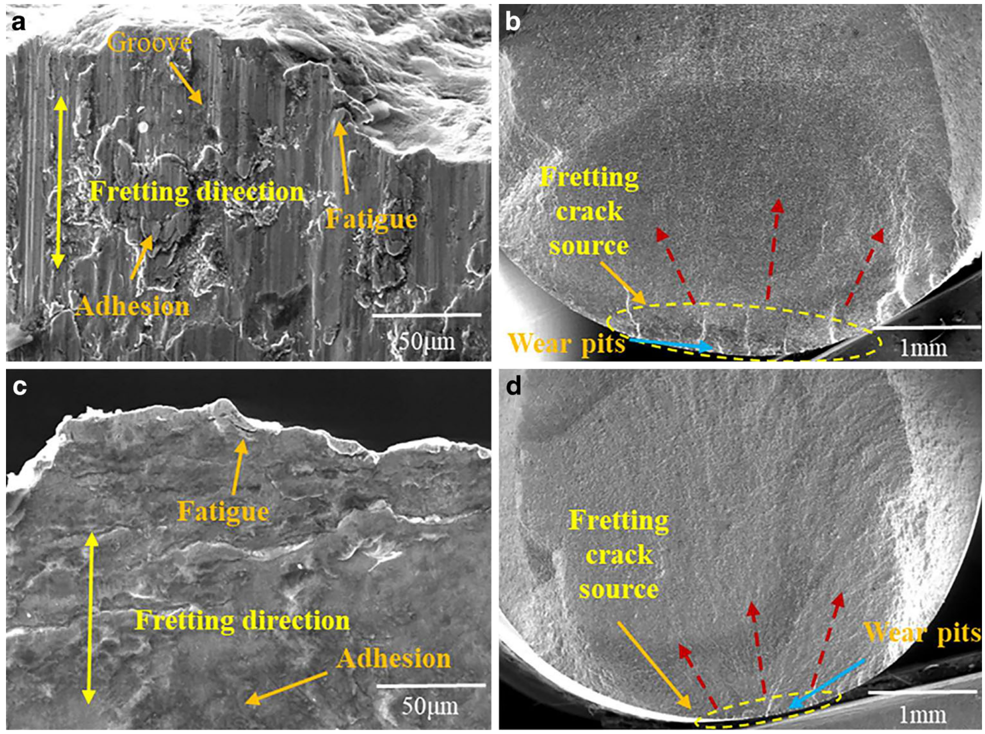


Fig. 11 Fatigue fracture. **a**,**b** Untreated sample; **c**,**d** UABB sample

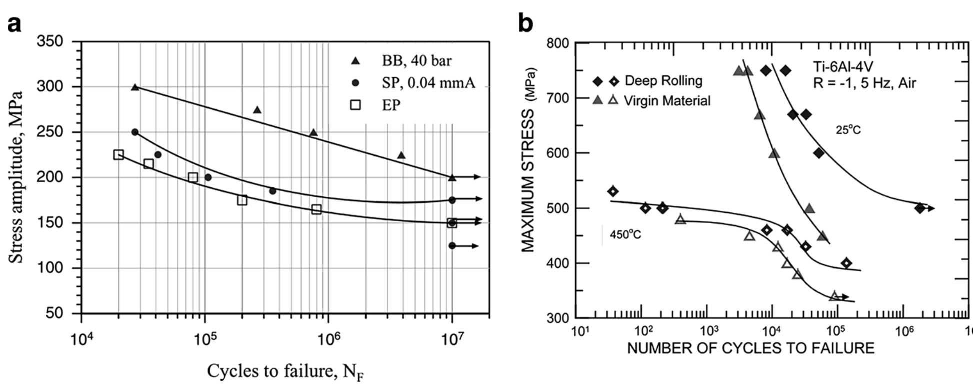


Fig. 12 S/N curves. **a** BB (i.e. LPBB), SP (i.e. shot peening) and EP (i.e. untreated sample) [73]; **b** Deep rolling (i.e. LPBB) and untreated samples at room and elevated temperatures [69]

down the fatigue crack initiation and fretting wear. Rodríguez et al. [53] reported the effect of the CRBB process on the low-cyclic rotating bending fatigue life of AISI 1038 steel. Surface micro-hardness was found to have a resolved correlation with fatigue life at all tested maximum stress levels. Muñoz-Cubillos et al. [70] researched the fatigue behavior of AISI 304 steel and AISI 316 steel through LPBB process. The results showed that the fatigue life of the sample was significantly promoted by the LPBB process. They observed that an increase in the volume fraction of martensitic phases in the microstructure and an increase in surface micro-hardness became the key factors leading to the enhancement of the low-cycle fatigue life of the LPBB sample due to the release of residual stress from the overcyclic load (around and above yield limit).

4.3 The effect of surface residual stress on fatigue behavior

The surface residual compressive stress could increase the fatigue life of the sample, while the surface tensile residual stress could decrease the fatigue life [71, 72]. In ball burnishing process, it was an effective method to improve the fatigue behavior of the sample by increasing the surface residual compressive stress.

Fouad et al. [73] explored the influence of mechanical surface treatments on the fatigue life of ZK60 magnesium alloy and found the fatigue strength of shot peening(SP) and LPBB samples increased by about 15% and 30%, respectively, compared to untreated sample, as shown in Fig. 12a. Further, the fatigue crack nucleation location of the sample was shifted from the surface to the subsurface region after LPBB and SP process, where the depth of the fatigue

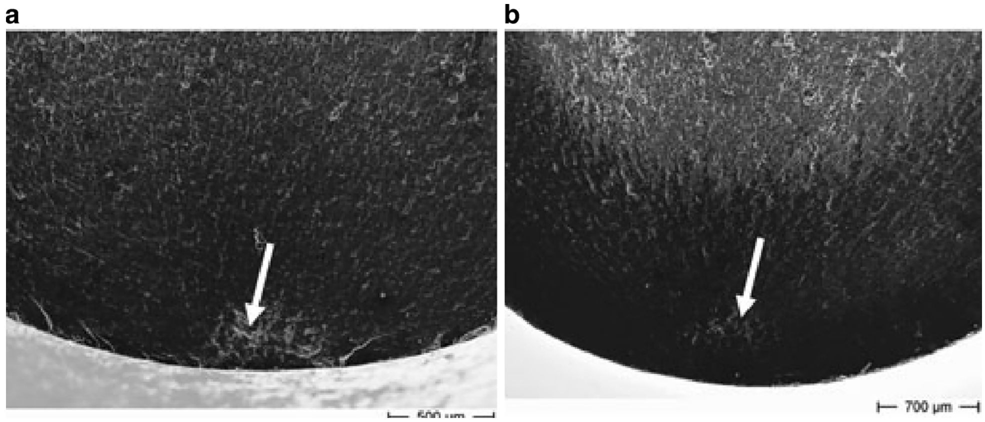


Fig. 13 Fracture surfaces showing subsurface crack nucleation [73]. **a** SP process; **b** LPBB process

crack nucleation location of the LPBB sample was greater, as shown in Fig. 13. They attributed both the increase in fatigue strength and the transfer of fatigue crack sources from the surface to the subsurface to the introduced surface residual compressive stress. However, when fatigue testing is performed under excessive loads or special operating conditions, the surface residual compressive stresses may be released to varying degrees. For example, Nalla et al. [74] improved high and low cycle fatigue behaviors of TC4 titanium alloy by LPBB process in Fig. 12b. They observed that the surface residual compressive stress was the main factor affecting the fatigue behavior of the sample. But in further studies, they found that a marked relaxation of these surface residual stresses occurs on fatigue cycling. The maximum compressive stress level after fatigue cycling decreased by about 30% at room temperature, while the maximum compressive stress after fatigue cycling at 450 °C showed almost complete relaxation. In addition, although the fatigue life of the burnishing sample decreased due to the almost complete release of surface residual compressive stress at a high temperature of 450 °C, it was still higher than that of the untreated sample. To explore the effect of cyclic loading on residual stress in fatigue testing, Mao et al. [75] studied the influence of different stress and strain amplitudes on the residual stress by UABB process. The results showed that the residual compressive stress was

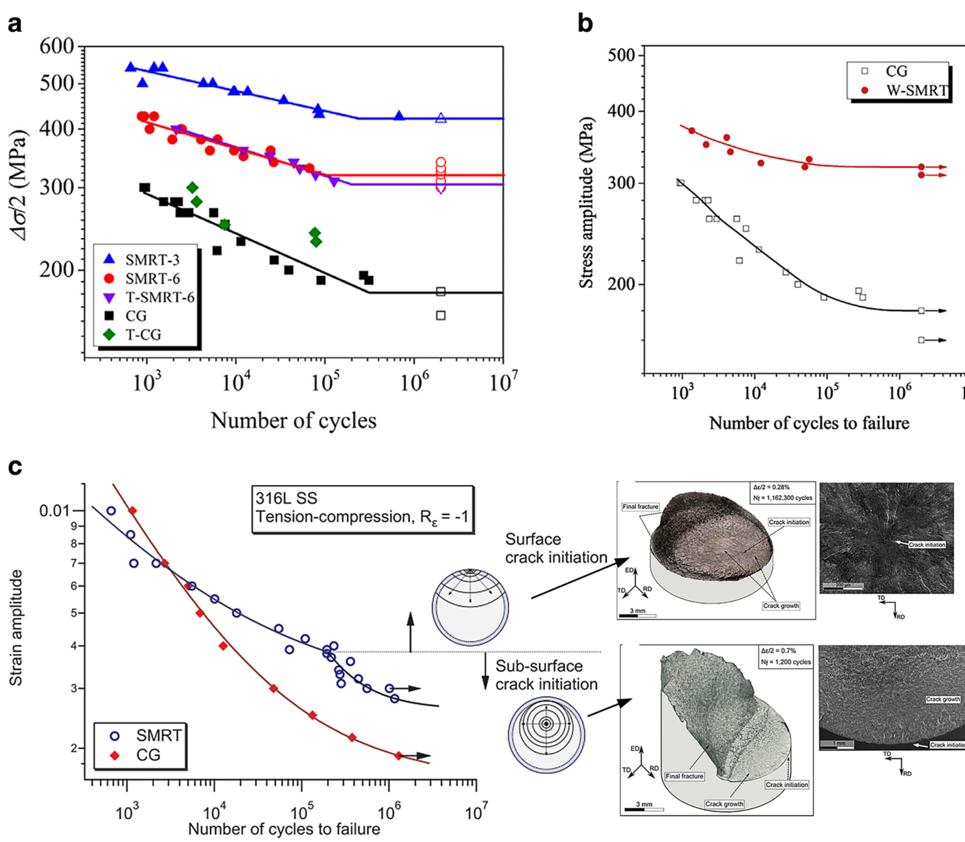


Fig. 14 S/N curves and fatigue fracture. **a** S/N curves of SMRT (i.e. LPBB) sample, SMRT sample after applying 3% prestrain(i.e. T-SMRT) and CG sample [63]. **b** S/N curve of W-SMRT (i.e. HTBB) sample and CG sample [78]. **c** S/N curve of SMRT (i.e. LPBB) sample and CG sample, Fatigue fracture of SMRT (i.e. LPBB) on the surface and subsurface [79]

released rapidly to a stable value after a small number of cycles, and the stable value of residual compressive stress also kept decreasing with the increase of stress amplitude or strain amplitude. They believed that the rapid release of residual stress at the initial stage was caused probably by excessive static load, that is, when the superposition of residual stress and external loading stress exceeded the yield strength of the material, the residual stress could be released and redistributed [76, 77].

4.4 The effect of surface microstructure on fatigue behavior

Generally, the surface microstructure after ball burnishing process has a positive effect on the fatigue life of the sample [69, 70, 73]. Since the GNS layer has been proposed [62], many researchers have prepared the GNS layer on the sample surface by ball burnishing process to deeply investigate the effect of surface microstructure on fatigue behavior.

For example, Lu et al. [63] prepared the GNS surface layer on the surface of 316L stainless steel by LPBB process, and explored the fatigue behavior of the sample of the GNS surface layer. The results showed that the fatigue limit of the sample of the GNS surface layer was increased to 320 MPa compared with the coarse-grained (CG) sample (180 MPa), as shown in Fig. 14a. Secondly, to further investigate the effect of the GNS surface layer on the fatigue life, they released completely the surface residual compressive stress by applying 3% pre-strain to the LPBB sample, as shown in Fig. 15a. However, the unchanged fatigue life before and after applying 3% pre-strain indicated that the residual compressive stress had little effect on the fatigue behavior in the sample of the GNS surface layer. Finally, to exclude the effect of phase transformation from austenite to martensite and the surface residual stress on the fatigue life at the same time, Lu et al. [78] carried out the surface treatment of the sample by HTBB process, and then cycled the HTBB sample 9×10^3 times at a strain amplitude of 0.4% before fatigue testing as shown in Fig. 15b. They found that the fatigue life was still improved significantly as shown in Fig. 14b. The same material was studied by Carneiro et al. [79] through the LPBB process, who found that the fatigue life of the LPBB sample was higher than that of the CG sample when the strain amplitude was below 0.6%, while the law was just the opposite when the strain amplitude was above 0.6%. In addition, when the strain amplitude was less than 0.39%, the fatigue source of the LPBB sample was generated on the subsurface, on the contrary, the fatigue source of the LPBB sample was generated on the surface, as shown in Fig. 14c.

5 Conclusions and future directions

The effects of parameters on the surface integrity and surface integrity on the fatigue behavior by the ball burnishing process are mainly reviewed. It can be seen from the literature that the lower surface roughness and stress concentration, the higher surface micro-hardness and residual compressive stress and a larger depth of plastic deformation layer can be made on the sample surface by the ball burnishing process. Generally, the residual compressive stress is considered to be the main reason for the improvement of fatigue behavior in the ball burnishing process. In addition, the phenomenon of grain refinement and increased dislocation density also appear in the surface microstructure. Among them, the sample with the GNS surface layer has excellent behavior in the fatigue test. However, there are still some problems in its preparation:

- The influence of shape and structure of the part on the preparation of the GNS surface layer by the ball burnishing process isn't considered in the research. For the complex part, how to prepare the GNS surface layer on the surface of the part while ensuring the accuracy and surface flatness of the part still needs to be further researched.
- At present, many composite processes are used for the preparation of the GNS surface layer of different ma-

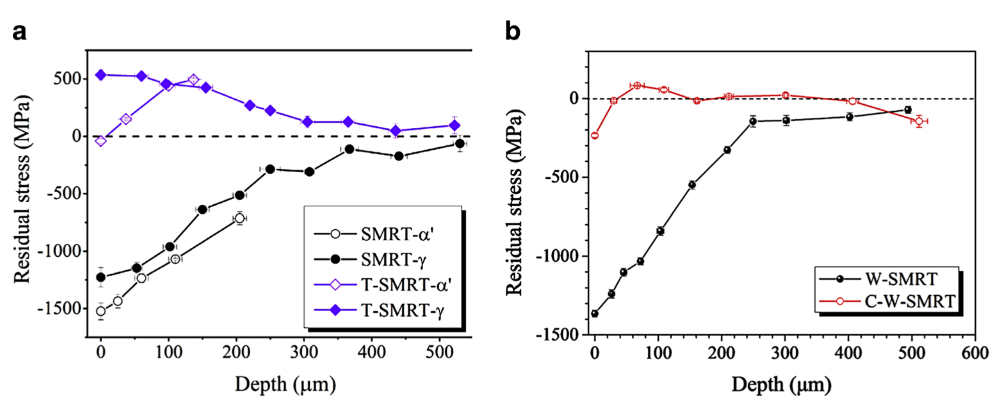


Fig. 15 In-depth residual stress distributions [78]: **a** SMRT (i.e. LPBB) sample and SMRT sample after applying 3% pre-strain (i.e. T-SMRT) [63]. **b** W-SMRT (i.e. HTBB) sample and W-SMRT sample cycled ~9×10^3 times at $\Delta\varepsilon_t/2 = 0.4\%$ (i.e. C-W-SMRT)

terials, such as cryogenic ball burnishing process, high-temperature ball burnishing process and so on. However, these new technologies still have certain limitations, and a systematic study of the effect of composite processes on the surface micro-structure must be carried out.

- The relationship between the GNS surface layer of different materials and parameters is still unclear. It is necessary to establish a mapping relationship and theoretical model between the process parameters and the surface microstructure through more in-depth and systematic research, so as to provide more powerful theoretical guidance and technical support for the preparation of the GNS surface layer of different materials.

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Conflict of interest Y. Zhou, X. Chu, J. Sun, J. Gao and L. Yang declare that they have no competing interests.

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