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REVIEW

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Effect of Machined Surface Integrity on Fatigue Performance of Metal Workpiece: A Review

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Abstract

Fatigue performance is a serious concern for mechanical components subject to cyclical stresses, particularly where safety is paramount. The fatigue performance of components relies closely on their surface integrity because the fatigue cracks generally initiate from free surfaces. This paper reviewed the published data, which addressed the effects of machined surface integrity on the fatigue performance of metal workpieces. Limitations in existing studies and the future directions in anti-fatigue manufacturing field were proposed. The remarkable surface topography (e.g., low roughness and few local defects and inclusions) and large compressive residual stress are beneficial to fatigue performance. However, the indicators that describe the effects of surface topography and residual stress accurately need further study and exploration. The effect of residual stress relaxation under cycle loadings needs to be precisely modeled precisely. The effect of work hardening on fatigue performance had two aspects. Work hardening could increase the material yield strength, thereby delaying crack nucleation. However, increased brittleness could accelerate crack propagation. Thus, finding the effective control mechanism and method of work hardening is urgently needed to enhance the fatigue performance of machined components. The machining-induced metallurgical structure changes, such as white layer, grain refinement, dislocation, and martensitic transformation affect the fatigue performance of a workpiece significantly. However, the unified and exact conclusion needs to be investigated deeply. Finally, different surface integrity factors had complicated reciprocal effects on fatigue performance. As such, studying the comprehensive influence of surface integrity further and establishing the reliable prediction model of workpiece fatigue performance are meaningful for improving reliability of components and reducing test cost.

Keywords: Surface integrity, Machining, Fatigue performance, Reciprocal effects

1 Introduction

The requirements of high reliability and long service life are increasingly stringent for mechanical components used in aerospace field. Fatigue fracture is a main failure mode of mechanical components subjected to cyclical mechanical and thermal loads, and fatigue failure is generally sudden and can lead to disastrous results. According to the statistics of Cowles B in 1996 (Figure 1), fatigue-related failures account for 49% of all typical component failure modes in military gas turbine engines [1]. Therefore, fatigue performance is critical for the mechanical components subjected to cyclical stresses. Experiments prove that fatigue cracks are usually initiated from free surfaces. Thus, fatigue performance was highly dependent on the integrity of machined surface [2–4]. Consequently, great efforts have been exerted by researchers to improve the fatigue performance of machined components by enhancing their surface integrity, such as by optimizing machining parameters and developing new inserts [5]. The fatigue strength of surfaces obtained by different kinds of machining processes

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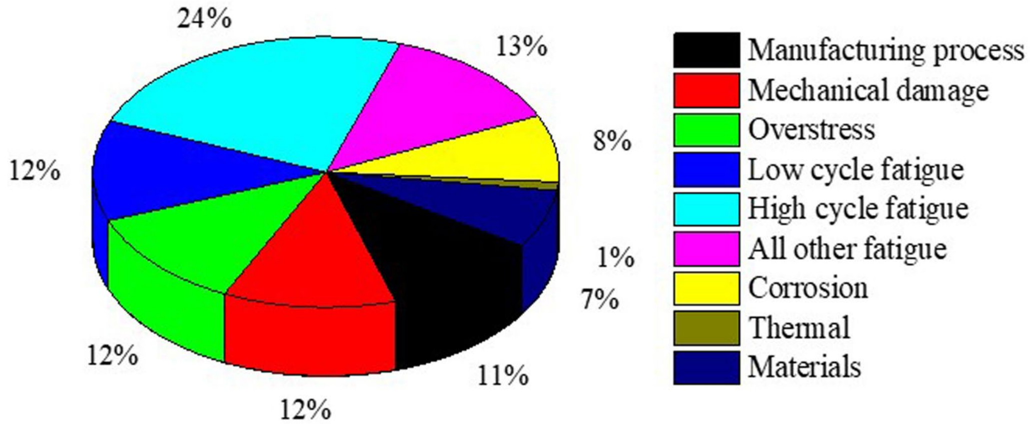

Figure 1 Representative jet engine component distress mode statistics [1]

has been compared to assist in the selection of processing technology (Table 1) [6–20]. In addition, the effects of machining parameters of certain machining technology, such as cutting speed [3, 21–24], feed rate [4, 22, 25–27], tool rake angle [28], and tool wear [29], were investigated. In most studies about the fatigue performance of machined components, the machined surface integrity, including the surface topography (e.g., surface roughness, local defects and inclusions) [30–33], residual stress [28, 34, 35], work hardening [36–39], and metallurgical structure changing [40–42], was considered as the bridge to reveal the internal mechanism of changed fatigue performance of a workpiece. However, disagreements are still observed in these studies because the tested workpiece materials, which covered steel [6–10], stainless steel [18], titanium alloy [15, 17, 20], Ni-base superalloy [13], and aluminum alloy [19], fatigue performance testing methods, and loading magnitudes vary (Table 1).

To express the research status and guide future research work in improving the fatigue performance of machined metal components, this paper will summarize the published data that addressed the effects of machined

Table 1 Effect comparison of machining technology on the fatigue performance

Processes	Material	Fatigue testing method	Better process	Paramount surface integrity
Turning vs. grinding	AISI 52100 steel [6]	Axial	Turning	Residual stress
	AISI 52100 steel [7]	Rolling contact	Turning	Not clear
	AISI 52100 steel [8, 9]	Rolling contact	Turning	Residual stress
	JIS SUJ2 steel [10]	Axial	Turning	Surface roughness, work hardening
Turning vs. ECM	γ-titanium aluminide alloy [11]	Not clear	Turning	Residual stress
Milling vs. grinding	γ-titanium aluminide alloy [12]	Four-point bending	Milling	Residual stress
	Ni-base alloy [13]	Axial	Milling	Surface roughness
Milling vs. grinding, polishing	En19 steel [14]	Three-point bending	Polishing	Surface roughness
	Titanium alloy [15]	Four-point bending	Not clear	Non-uniformly distributed carbides
Milling vs. EDM	SAE J438b steel [16]	Three-point bending	Milling	Residual stress, phase transform
	Titanium alloy [17]	Axial	Milling	Surface roughness, recast layer
	AISI 304 stainless steel [18]	Four-point bending	EDM	Not clear
EP vs. SP, RB and DR	Titanium, aluminum, magnesium alloy [19]	Axial and rotating bending	Depend on the material	
EDM vs. LBM, AWJM, milling, grinding and SP	Titanium alloy [20]	Three-point bending	SP	Residual stress

Note: ECM means electro-chemical machining, EDM means electro-discharge machining, EP means electrolytical polishing, SP means shot-peening, RB means roller-burnishing, DR means deep-rolling, LBM means laser-beam machining and AWJM means abrasive water-jet machining.

surface integrity on the fatigue performance of metallic materials. The effects of surface topography, residual stress, work hardening, and metallurgical structure changes will be detailed individually, and their reciprocal effects will be discussed. The limitations in existing studies and the future directions in anti-fatigue manufacturing field will be summarized.

2 Effect of Surface Topography on Fatigue Performance

The effects of surface topography, including the surface roughness, local defects and inclusions, on workpiece fatigue performance have been studied in the early 1930s [4], and several agreements have been reached to data.

First, the surface roughness, local defects, and inclusions on the machined surface could affect the fatigue performance of a workpiece [16, 30–33, 43, 44]. The large surface roughness, local defects, and inclusions could degrade the fatigue performance of a workpiece [21, 34, 45–48].

Second, the surface topography mainly affects crack initiation and has no obvious effect on crack propagation [49–51]. Therefore, most studies stated that surface topography was mainly related to the high-cycle fatigue performance because the high-cycle fatigue performance mainly depended on the crack initiation stage, and the crack propagation life accounts for the main part of the low-cycle fatigue performance [16, 52, 53].

Finally, the influence degree of surface topography was determined by workpiece material properties [54–56], workpiece geometry [51], and loading stress magnitude [24, 57]. Figure 2 summarized the fatigue limits of several materials (e.g., iron, Ni-based alloy and titanium alloy) under different surface roughness generated by varying machining conditions [54]. Under gentle machining conditions, the endurance limit of AISI 4340 steel changed significantly with various surface roughness, whereas the endurance limit of Inconel 718 was not dependent on surface roughness.

2.1 Effect of Surface Roughness on Fatigue Performance

In earlier studies, the arithmetic average height of the surface profile, *Ra*, was generally considered the only factor that affected the fatigue performance of machined workpieces [58, 59]. As research progresses, increasing researchers emphasized that *Ra* cannot characterize all surface topography features that were important to the fatigue performance [60]. In subsequent studies, the surface profile height parameters, such as *Rz* (maximum height of profile), *Rz*″ (maximum height of stochastic surface roughness curve), and *Rt* (total height of profile) [13, 14, 61]; The hybrid parameters, such as Δq (root mean square slope) and λq (spacing between local peaks and valleys) [61]; the 3D surface topography parameters, such as *Sa* (arithmetic mean surface height), *Std* (texture direction) and *Sal* (the fastest decay autocorrelation length); and the volume parameters, such as *Sci* (core fluid retention index), *Svi* (valley fluid retention index), and *Ssc* (arithmetic mean summit curvature of the surface) [62, 63], were relevant to fatigue strength.

However, the most effective indicator was controversial (Table 2). Bayoumi et al. [61] investigated the

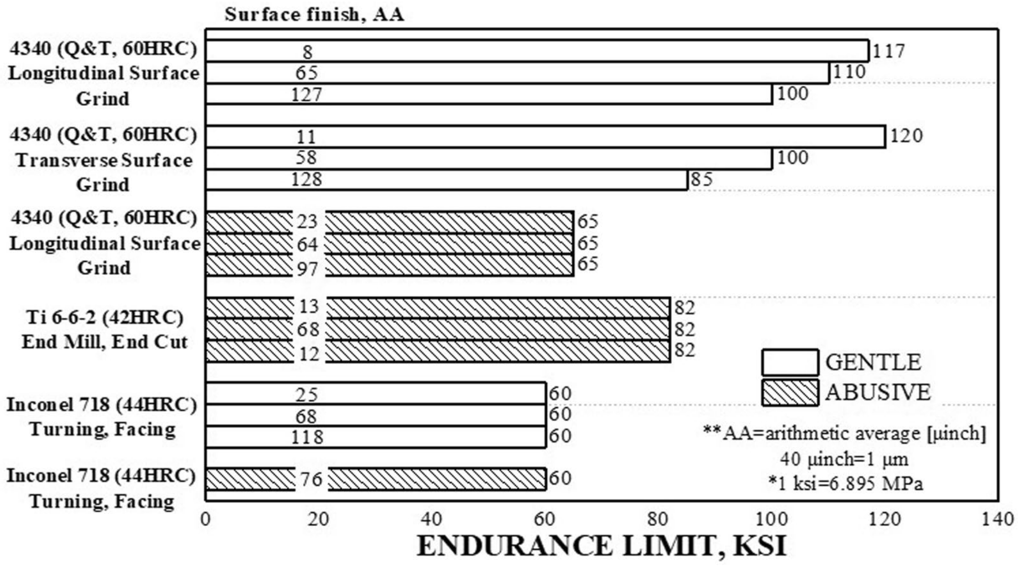

Figure 2 Effect of surface roughness on fatigue performance of various materials [54]

Table 2 Most effective indicator of surface roughness on workpiece fatigue life

Researcher	Material	Fatigue testing method	Most effective indicator
Bayoumi et al. [61]	Aluminum alloy	Rotating bending	Amplitude parameters (*Ra* and *Rq*)
Taylor et al. [14]	Steels and non-ferrous alloys	Three-point bending	Height parameters (*Rz* and *Rt*)
Siebel [64]	Steels	Axial	Height parameters (*Rt*)
Yang et al. [21]	Titanium Alloy	Axial	Three-dimensional parameters
Abroug et al. [62]	AA7050 alloy	Plane bending	*Sa*

correlation between the surface roughness parameters and the rotating bending fatigue endurance limit of an aluminum alloy and found that the amplitude parameters (e.g., *Ra* and *Rq* (root mean square height of the surface profile)) were more important in affecting fatigue endurance limit than the height (e.g., *Rz* and *Rt*) and hybrid parameters (e.g., Δq and λq). Nevertheless, Taylor et al. [14] stated that the effects of height parameters (e.g., *Rz* and *Rt*) on the fatigue performance were the most significant among all the roughness parameters after testing the fatigue performance of various steels and non-ferrous alloys. Siebel [64] also believed that the effect of height parameters was crucial because they found that when the groove depth exceeded the critical value (*Ro*), the reduction in fatigue endurance limit was proportional to log *Rt* (Figure 3). In addition, Yang et al. [21] suggested that the fatigue life models based on surface stress concentration factor that was calculated by using three-dimensional surface roughness parameters were more accurate than that using two-dimensional ones. Abroug et al. [62] stated that the 3D amplitude parameters *Sa* characterized the fatigue behavior of milled surfaces the best.

Griffiths [63] also summarized the influence degree of different surface roughness parameters on the fatigue performance of workpieces by conducting a comprehensive survey over the existing studies, and the results are shown in Table 3.

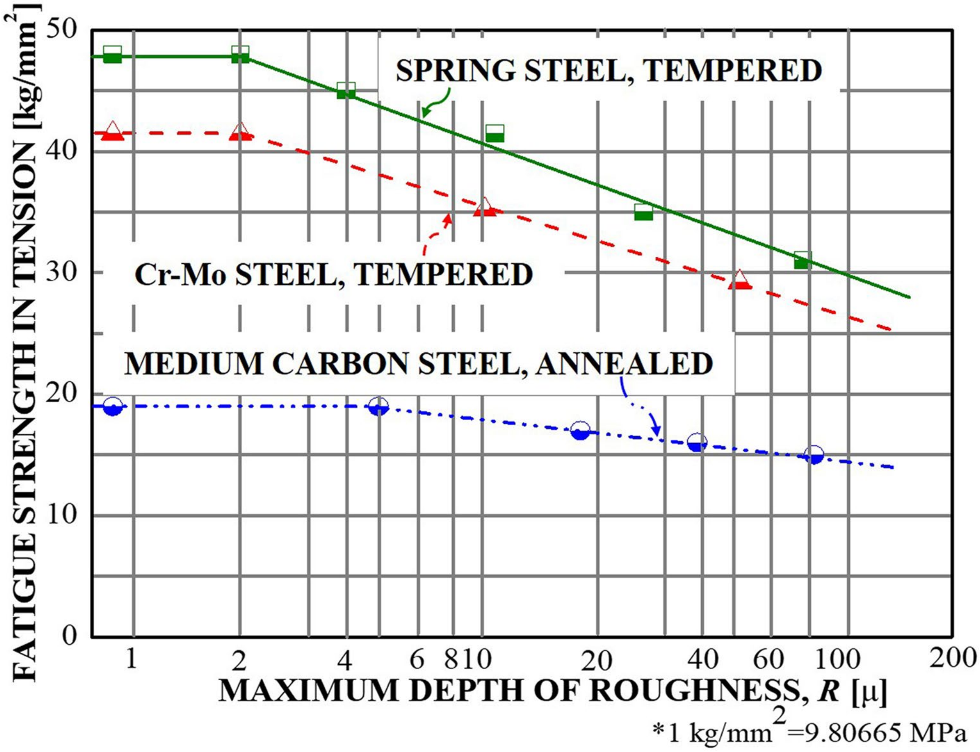

Figure 3 Fatigue strength in tension of various steels as a function of surface roughness [64]

Table 3 Influence degree of surface roughness parameters on workpiece fatigue life [63]

Parameter	Effect
Heights *Ra*, *Rq*, *Rt*, *Sa*, *Sq*	Much
Distribution and shape *Rsk*, *Rku*, *Ssk*, *Sku*	Some
Slopes and curvature *RΔq*, *SΔa*	Little
Lengths and peak space *Rsm*, *HSC*	Little
Lay and lead *Std*, *Sal*	Much

2.2 Effect of Other Topography Parameters on Fatigue Performance

Aside from the surface roughness, the sharpness of profile [31, 65], the size and shape of local defects [33, 66, 67], the shape and direction of machining marks [14, 35], the size and location of inclusions [32, 43] and the size of microcracks [11, 68, 69] were also proven to be influential on fatigue performance. Leverant et al. [65] proposed that the sharpness (e.g., profile valley radius) of machining grooves was more critical than the maximum height of the profile (*Rz*) when studying the fatigue properties of Ti-6A1-4V titanium alloy. Warhadpande and Sadeghi [31] confirmed the important effects of surface dent sharpness on the rolling contact fatigue life. Taraf et al. [33] investigated the effects of size and shape of surface defects on the railway wheel fatigue damage and found that the fatigue life of workpieces with circular defects was longer than those with elliptical defects. The increased size of defects could degrade fatigue performance substantially. Several studies [11, 68, 69] revealed that the machining-induced microcracks may propagate directly to cause fatigue failure, although some disagreements about the critical value of microcracks in these studies were addressed.

Güngör and Edwards [32] compared the effect degree of inclusions and surface roughness on the fatigue performance of forged 6082 aluminum alloy and found that the inclusions with a diameter of 20–80 μm at the specimen surface could act as crack nucleation sites. Deng et al. [70] also found the fatigue cracks that initiated from the inclusions when the fatigue fracture surfaces of carburized 12Cr2Ni were observed (Figure 4). These results agreed well with some other researchers who suggested that if the size of the surface inclusions was an order of magnitude higher than the *Ra* value, then they could outweigh any effect on fatigue performance because of surface roughness [4, 15]. Hereby, Saberifar et al. [43] stated that for a given stress, the critical inclusion size for crack nucleation could be increased by eliminating the surface roughness.

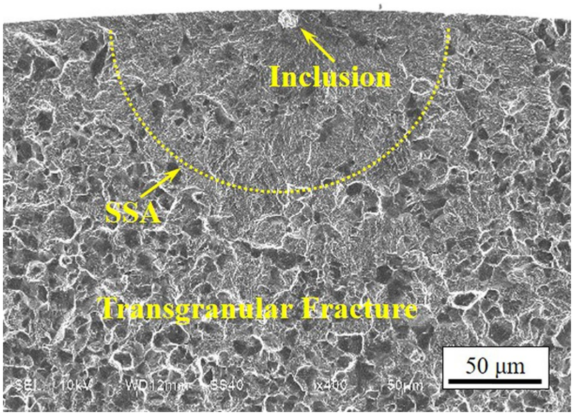

Figure 4 Fracture surface of a fatigue crack which initiated from an inclusion [70]

2.3 Limitation

The main limitation that exists in the aforementioned studies is that the effects of surface topography on fatigue performance have not been described well using appropriate indicators or methods.

Given that the surface topography mainly affects the material fatigue performance by resulting in stress concentration, the stress concentration factor (K_t) was adopted by many researchers as the aggregative indicator to represent the comprehensive influence of surface topography [71]. Several models and methods were presented to calculate the K_t. Based on the equation of K_t for a single surface notch in a panel subjected to uniform tension (i.e., Eq. (1)), Neuber [72] proposed the semiempirical equation of K_t using standard roughness parameters (Eq. (2)):

$$K_t = 1 + 2\sqrt{\frac{t}{\rho}}, \tag{1}$$

where t is the notch height and ρ is the notch root radius.

$$K_t = 1 + n\sqrt{\lambda\frac{R_z}{\rho}}, \tag{2}$$

where n represents the stress state ($n=1$ for shear and $n=2$ for tension). Rz and ρ are the 10-point surface height and notch root radius, respectively. λ is the ratio between spacing (b) and height (t) of surface irregularities, $\lambda = b/t$ (Figure 5).

Arola et al. [73] developed a new model to calculate the effective stress concentration factor ($\overline{K_t}$) of machined surface texture (Eq. (3)). The arithmetical average roughness (*Ra*), peak-to-valley height (*Ry*), 10-point surface

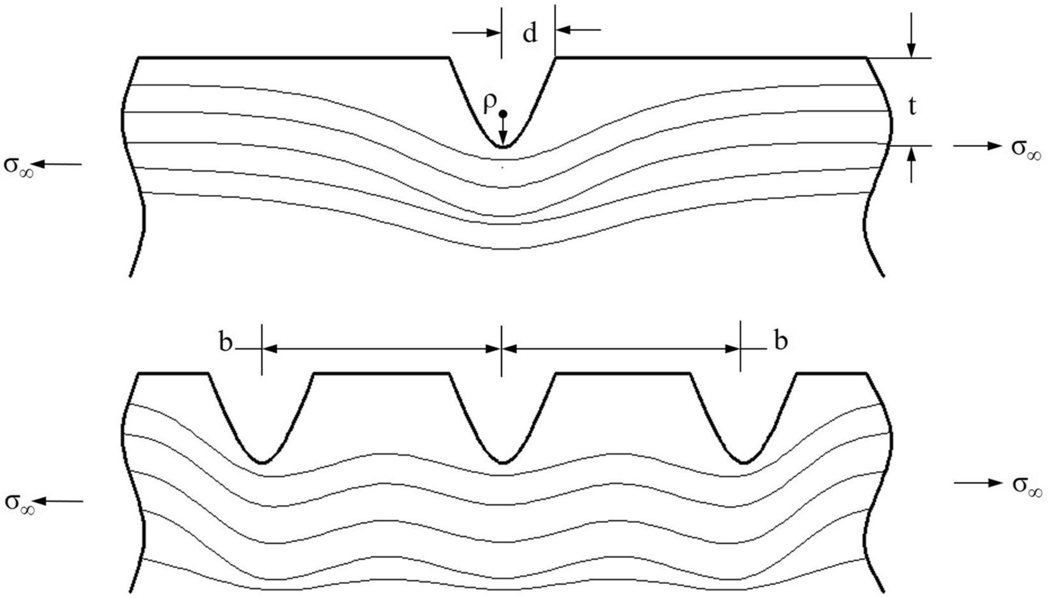

Figure 5 Near-notch stress trajectories for single and multiple surface notches [57]

height (Rz), and effective profile valley radius ($\overline{\rho}$) were considered.

$$\overline{K_t} = 1 + n\left(\frac{R_a}{\overline{\rho}}\right)\left(\frac{R_y}{R_z}\right), \tag{3}$$

where n is the empirical constant that represents the stress state as well ($n=1$ for shear and $n=2$ for tension).

Except for the aforementioned mathematical model, the finite element (FE) analysis was also adopted to obtain the machined surface stress condition [44, 60, 71, 74]. The sample surface profile was measured and used to generate the FE model. Uniform tensile load was applied after defining the material properties and meshing. The maximal and normal von Mises equivalent stresses were extracted, and the stress concentration factor (K_t) was determined by using Eq. (4).

$$K_t = \frac{\sigma_{max}}{\sigma_{nom}}, \tag{4}$$

where σ_{max} and σ_{nom} are the maximal and normal von Mises equivalent stress, respectively. The principle of getting σ_{max} and σ_{nom} by finite element calculation is shown in Figure 6.

However, although the stress concentration factor (K_t) was a useful indicator to reveal the effect mechanism of surface topography on fatigue performance to some extent, it still has some defects.

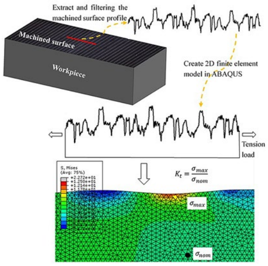

Figure 6 Principle of finite element calculation to determine stress concentration factor [60]

First, the stress concentration factor could not effectively describe the effects of microcracks that can propagate directly to cause fatigue failure. In addition, the stress concentration factor did not consider the material properties, the shape and direction of machining marks, and the critical value of surface roughness, defects, and inclusions. The effect degrees of surface topography on fatigue performance differed for various workpiece material properties [54], and machining defect shapes [14, 35]. Finally, the stress concentration factor (K_t) attributed the effects of surface topography to the notch effect wholly. However, some researchers found that the true effect of surface topography on fatigue performance was not as notable as that of the stress concentration factor [75, 76]. Taylor and Clancy [14] proposed that the fracture mechanics approach led to better results than the notch effect mechanism for low roughness surfaces, in comparing the fatigue life of En19 steel machined by polishing, grinding, milling and shaping.

Therefore, a more effective indicator that can fully characterize the influence of surface topography on machined workpiece fatigue performance needs to be explored further.

3 Effect of Residual Stress on Fatigue Performance

With the deep research in machined surface fatigue performance, many researchers suggested that the residual stress was also an important factor that affected the workpiece fatigue property aside from surface topography [10, 20, 28, 34]. For the effects of residual stress on fatigue performance, the researchers had reached an agreement that the compressive residual stress can improve fatigue limit and the tensile residual stress can reduce fatigue resistance [15, 16, 30, 35, 77–79]. In the literature, tensile residual stress was identified as a significant factor that resulted in the poor fatigue performance of electro-discharged and laser-beam machined surfaces [17, 30, 80]. On the contrary, the compressive residual stress was widely used to explain the improved fatigue limit of surfaces produced by shot peening [81–85], turning [6, 11, 26], milling [12, 76, 86], and abrasive waterjet machining [20, 30]. Smith et al. [6] and Koster [54] even considered that the effects of residual stress on fatigue performance were more significant than those of surface topography. El-Helieby and Rowe [87] also found that the relationship between the surface residual stress and the fatigue strength of ground En31 steel was approximately linear.

3.1 Influence Mechanism and Critical Indicators of Residual Stress

Although the influence mechanism of machined surface residual stress on fatigue performance has been widely investigated, it is still controversial. Most researchers agreed with the conclusion of Wagner and Gregory [49] that compressive residual stress could retard crack growth significantly, but its effect on crack initiation was insignificant. Some researchers [11, 88, 89] believed that compressive residual stress could reduce the fatigue crack growth rate and thus improve the workpiece fatigue performance. Guo and Warren [8] suggested that the compressive residual stress could impede crack growth by closing the crack tip. However, some researchers compared the location of crack initiation of samples and found that the compressive residual stress could affect the fatigue crack initiation as well. Compressive residual stress could force the movement of the location of fatigue crack initiation from the sample surface to the subsurface [75, 84, 90, 91].

The disagreement on the influence mechanism of residual stress resulted in the argument on the most critical indicators of residual stress that determined the fatigue performance. The typical residual stress depth profile on the machined surfaces is as shown in Figure 7 (Obtained with hard turned bearing steel). Regardless whether the residual stress was tensile or compressive on the surface, it fell off to a maximum compressive state with an increase in depth. Subsequently, the compressive residual stress decreased gradually until a steady value was achieved in the near workpiece substrate [92–94].

Given that residual stress mainly affects crack growth but has no obvious effect on crack initiation, Koster [54] suggested that the subsurface residual stress controlled the workpiece fatigue behavior rather than the outer surface stress. However, Hua et al. [94] found that the surface principal residual stress could result in crack closure during cyclic loading and decreased crack propagation rate. Schwach et al. [95] stated that the surface residual stress value and the near-surface residual stress profile were significant for rolling contact fatigue. However, the depth of the maximum compressive residual stress in the subsurface was not crucial. Conversely, Drechsler et al. [96] and Hassan et al. [97] both suggested the importance of magnitude and influence depth of compressive residual stresses for the fatigue performance of a rotating beam. This result was supported by Wagner [19] and Klotz et al. [82], who found that high-cycle fatigue cracks nucleated at the position with the maximum tensile residual stress below the machined surface (Figure 8 (Obtain with shot peened Inconel 718)).

3.2 Residual Stress Relaxation

Although residual stress relaxation has been recognized to be non-negligible in analyzing the effect of residual stress on fatigue performance of workpiece, its effect degree was controversial [34, 81, 83]. Benedetti et al. [98] studied the reverse bending fatigue behavior of a shot peened 7075-T651 aluminum alloy and found that residual stress relaxation only existed when the material plastic flow stress was achieved in the compressive part of the loading cycle. This result agreed well with Hempel et al. [99] and Liu et al. [100], who all suggested that once the summation of residual stress and applied stress reached or exceeded the yield strength of workpiece material, the residual stress could mostly be released in several cycles, thereby resulting in the negligible effect of residual stress on fatigue performance. Based on this important finding, most researchers suggested that machined surface residual stress mainly affected the high-cycle fatigue (low-stress fatigue) [16, 101].

However, Ozdemir et al. [102] and Dalaei et al. [103] found that the relaxation of compressive residual stress could also occur under cyclic loadings even when the total loading is below the yield strength of the material. Zhuang et al. [104] and Torres et al. [105] suggested that residual stress relaxation was related to the applied stress value and the number of fatigue cycles, and an analytical model was proposed to estimate the residual stress relaxation (Eq. (5)):

$$\frac{\sigma_N^{re}}{\left|\sigma_0^{re}\right|} = A\left(\frac{2\sigma_a^2}{(1-R)\left(C_w\sigma_y\right)^2}\right)^m (N-1)^B - 1, \tag{5}$$

where $\left|\sigma_0^{re}\right|$ and σ_N^{re} are the initial surface residual stress and the surface residual stress after N cycles, respectively. A and m are material constants which dependent on cyclic stress and strain response. Constant B controls the relaxation rate versus loading cycles. σ_a is the cyclic load amplitude and σ_y is the material yield strength. C_w is a parameter which accounts for the degree of cold working. R is the loading ratio and N is the loading cycle.

Given the residual stress relaxation, Cretu and Popinceanu [106] suggested the existence of an optimum residual stress distribution that can achieve the best fatigue performance for a certain loading. However, the authors did not present the method for determining the optimum residual stress distribution.

4 Effect of Work Hardening on Fatigue Performance

In the machining processes, severe material plastic deformation could induce microstructure changes, including the storage of dislocations, grain refinement, and even phase transformation, thereby increasing the hardness of machined surface, also known as work hardening [107, 108]. Work hardening was closely associated with material fatigue performance [2, 8, 23]. According to the existing literature, the effect of work hardening on workpiece fatigue performance was an extremely controversial subject.

Jones et al. [109] explored the effects of strain hardening on the load bearing capacity of a rail steel and found that the material yield strength was proportional to its Vickers hardness (Eq. (6)):

$$k = \frac{\sigma_y}{\sqrt{3}} = \frac{H_V}{3\sqrt{3}}, \tag{6}$$

where k is the shear yield strength, σ_y is the yield strength and H_V is the Vickers hardness.

Choi [25] established a crack propagation life model to describe the fatigue performance of turned AISI 1053 steel by considering its material properties (Eq. (7)). The model shows that high surface hardness could result in long crack propagation life.

$$N_P = \int_{a_1}^{a_2} \frac{1}{C\frac{H_b}{H_l}(\Delta K)^n}\mathrm{d}a, \tag{7}$$

where N_P is the crack propagation life. a_1 and a_2 are the half length of initial and final crack, respectively. C is the material constant. H_b is the Knoop hardness of the bulk material, and H_l is the local Knoop hardness. ΔK is the stress intensity factor range at the leading tip. n is the slope index.

Murakami [110] further suggested that the material fatigue strength was proportional to its Vickers hardness and could be expressed by using Eq. (8). This result was adopted and confirmed by many researchers. Sasahara [35] studied the effects of work hardening on the fatigue performance of machined steel and stated that work hardening could improve its yield strength, thereby prolonging fatigue life. Nishida et al. [111] also found that work hardening can improve the fatigue strength of rolled S25C steel. Similar results on various metallic materials, such as the Ni-based superalloy [13, 30, 52], steel [83, 112], and stainless steel [113], were also

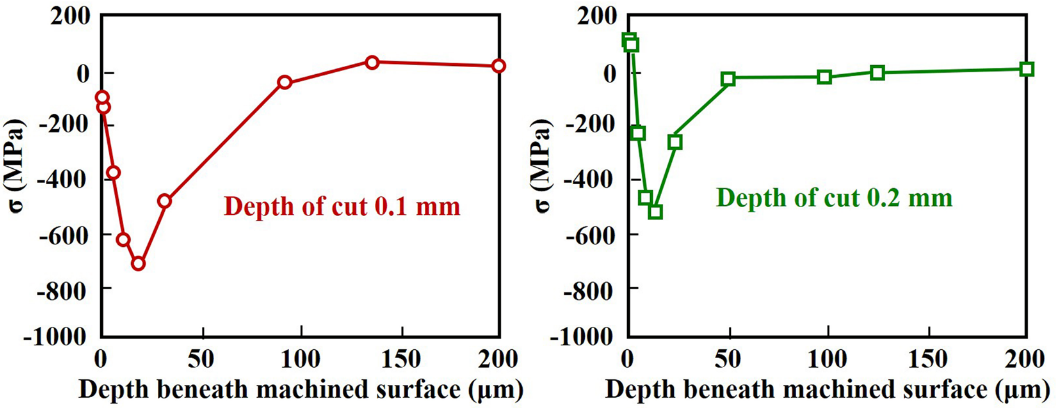

Figure 7 The typical residual stress depth profile with compressive (left) and tensile (right) surface residual stress [92]

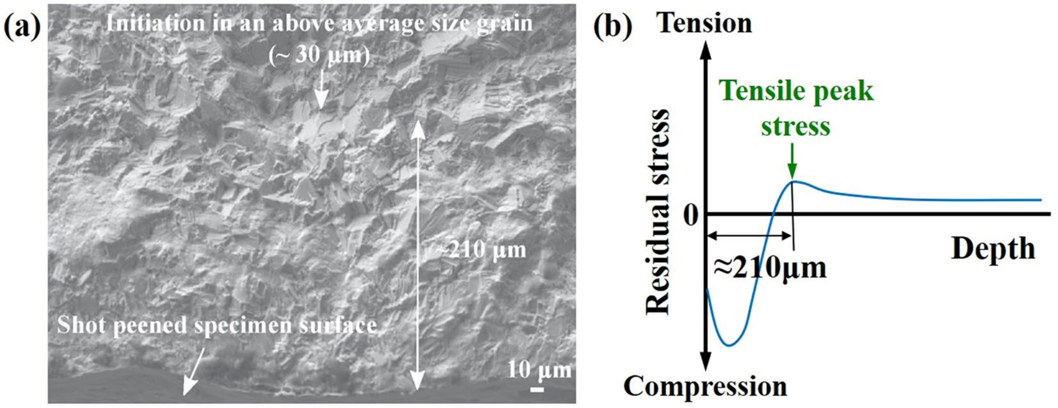

Figure 8 Crack initiation at the position with maximum tensile residual stress: **a** fractured surface and **b** residual stress depth profile [82]

obtained by researchers with different fatigue testing methods. Wagner [19] concluded that work hardening could inhibit fatigue crack initiation by increasing the yield strength, thereby improving the workpiece fatigue performance.

$$\sigma_{M,w} \cong 1.6H_V, \tag{8}$$

where $\sigma_{M,w}$ is the material fatigue strength and H_V is the Vickers hardness.

Inés et al. [114] compared the rotating bending fatigue performance of original, gas-nitrided and shop peened 42CrMo4 steel and found that the effect of surface work hardening on fatigue crack propagation behavior was more significant than the residual stress field. On the contrary, although Iswanto et al. [115] confirmed that the bending fatigue limit of rolled stainless steel increased with work hardening, they suggested that the effect of compressive residual stress on the fatigue limit improvement of stainless steel was higher than that of work hardening. Martin et al. [39] studied the fatigue life of shot peened AA 6005-T6 aluminum alloy and stated that the effect degree of roughness, residual stress field, and work hardening on fatigue behavior depends on the material properties. For high-strength materials, roughness and residual stress field are expected to be more important in the fatigue behavior of the material than the increase in surface hardness. For materials with good work hardening capability and moderate mechanical strength, the increase in hardness was more relevant than the other variables.

Many researchers also suggested that work hardening could reduce the ductility and fracture toughness of machined surface, thereby reducing the inhibition of fatigue crack propagation (Table 4) [9, 49, 116]. Klumpp et al. [36] tested the influence of work hardening on fatigue crack growth, effective threshold and crack opening behavior of Ni-based superalloy Inconel 718. High fatigue crack growth rate, low effective thresholds, and reduced crack opening stress intensities were observed in work-hardened material. Huang et al. [23] found that an appropriate surface strain hardening could contribute to the improvement of fatigue resistance. However, excessive surface strain hardening could increase surface brittleness and thus destroy fatigue resistance.

In addition, Mantle and Aspinwall [68] stated that the reduced ductility of material induced by work hardening was a barrier of producing defect-free surfaces. Once the machined surfaces contain microcracks, their fatigue performance would mainly depend on the crack propagation process and thus be reduced by work hardening [76, 86].

Fukui et al. found another adverse impact of work hardening on fatigue performance by studying the rolling contact fatigue endurance of high manganese austenitic steel [113]. They found that the fatigue cracks could be propagated easily along the boundary of the work hardening zone and the normal zone. The run-out of machined surface fatigue strength could be increased by work hardening because of the inhomogeneity of work hardening [12].

These observations suggested that the effect of work hardening on workpiece fatigue performance was two-faced and depended on the induced yield strength and fracture toughness. Liu et al. [100] tested the surface yield strength and fracture toughness of face-milled 17-4PH stainless steel by using the continuous ball indentation technique. It was found that the effect of work hardening on the surface yield strength and fracture toughness depended on its generating mechanism. When work hardening mainly resulted from plastic strain hardening, material fracture toughness seriously decreased and balanced the positive effect of increased yield strength on fatigue performance. However, when work hardening was mainly generated by grain refinement, the surface yield strength and fracture toughness increased simultaneously and prolonged the fatigue life. This result agreed well with that of Libor et al. [38], who used severe shop peening to induce grain refinement and produce a nanostructured surface layer on 50CrMo4 steel, which improved the fatigue strength by 23% in the ultra-high cycle fatigue regime (up to 10^9 cycles). They suggested that the nano-crystallized structure of the surface layer of material could increase the stress to be applied for crack initiation. Zhao et al. [117] ascribed the fine crystal strengthening effect to the grain orientation. They found that the elongated grains in nano-crystallized structure are basically parallel to the external load, that id, they were perpendicular to crack propagation surface. In this direction, the grain boundaries are adverse to the incubation of crack, and are less likely for fatigue crack to initiate from this layer. Some other studies [47, 79, 83, 118, 119] also found that grain refinement could improve material yield strength and ductile fracture toughness by suppressing the formation of martensite cracks and cleavage fracture. However, they did not provide effective control methods of work hardening to enhance the fatigue performance of machined components.

5 Effect of Metallurgical Structure Changes on Fatigue Performance

Aside from the grain refinement and metallurgical structure-changing induced work hardening, the effects of some other machining-induced metallurgical structure changes on machined workpiece fatigue performance were also studied by researchers.

Nishida et al. [111] suggested that the deformed laminated structure of roller worked steel JIS S25C improved fatigue strength compared with the non-roller worked specimens with laminated parallel structures. They considered that the deformed structure can prevent crack initiation and resist the propagation of fatigue cracks into the interior region during fatigue tests. Rio et al. [41] also believed that the grain boundaries could act as barriers to plastic flow in the zone ahead of the crack tip. However, Cox et al. [120] stated that the mismatched dislocations was harmful to the machined workpiece fatigue performance because the micro-cracks along unfavorably aligned basal planes in the alpha phase at the machined subsurface of metastable β titanium alloy Ti-5553 was the dominant crack initiation mechanism.

Table 4 The effect of surface layer properties on crack nucleation and propagation [49]

	Crack nucleation	Crack propagation
Surface roughness	Accelerates	No effect
Cold work	Retards	Accelerates
Residual compressive stress	Minor or no effect	Retards

The effects of martensitic transformation in the machined surface layer on the fatigue performance were investigated in several research. Chen et al. [121, 122] suggested that compared with the austenite structure, the transformed martensite tissue was harmful to the fatigue strength. The boundaries of martensite lath were conducive to crack propagation, which could reduce the workpiece fatigue performance. In addition, the austenite could sustain larger plastic deformation, and the martensitic transformation during fatigue process could absorb energy and relax the stress concentration at the crack tip, thereby hindering the propagation of fatigue cracks. However, Uematsu et al. [123] tested the rotating bending fatigue performance of cyclically pre-strained 304 austenitic stainless steel and found that the high-volume fraction and uniform distribution of martensitic phase induced the transition of crack initiation mechanism and increased fatigue limit. In addition, although the martensitic transformation reduced the fatigue strength of 304 stainless steel remarkably in 3%NaCl solution at −25 °C, Nakajima et al. [40] proved that the quantity of strain-induced martensitic phase did not affect the fatigue strength of 304 stainless steel in laboratory air condition. Their experiments confirmed that the quantity of martensitic transformation hardly influenced the crack growth behavior because the strain-induced martensitic transformation occurred in the slip bands and fatigue crack initiated within the austenitic phase.

As the result of severe plastic deformation or re-solidification of melted metal during thermal machining process, "white layer" is a kind of serious metallurgical structural changes. The effects of white layer on the workpiece fatigue performance were investigated specifically by some researchers. Although a few researchers [6, 124] suggested that the effect of white layer on high-cycle tension-tension fatigue performance was less significant than residual stress, most researchers believed that the white layer was severely detrimental to fatigue performance [125, 126]. The dendritic structure with micro-cracks in the white layer, which typically runs normal to the machined surface (Figure 9), could work as the crack initiation source [16]. In addition, the high brittleness of the white layer was conducive to the crack initiation and propagation and thus could destroy the fatigue performance. Shur et al. [126] proved experimentally that cracks were easier to form in the white layer and propagate along the boundary between the white layer and the substrate under the compressing load and plastic deformation. Schwach et al. [95] and Guo et al. [125] also confirmed a negative effect of white layer on fatigue performance by comparing the rolling contact fatigue lives of the samples with and without white layer. Their results showed that fatigue life severely decreased with the increased thickness of white layer.

Although the effects of metallurgical structure changes on the machined workpiece fatigue performance have been studied by many researchers, unified and exact conclusions have not been reached. The effective workpiece fatigue performance prediction model (or method) based on the metallurgical structure changes has not been established.

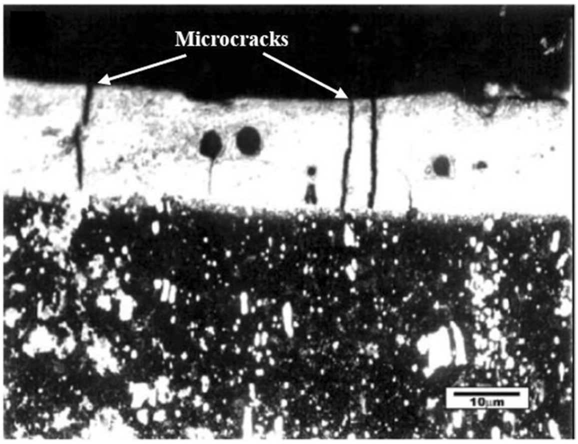

Figure 9 Cross section of an EDM sample with white layer [16]

6 Reciprocal Effect of Different Factors on Fatigue Performance

Although the effect of surface topography, residual stress, work hardening and metallurgical structure changes on machined workpiece fatigue performance was discussed separately above, the machining processes usually change these surface integrity factors synchronously [3, 82]. Given that all of these factors can change the fatigue crack initiation and propagation processes, reciprocal effects must exist among them. As such, the fatigue performance of the machined workpiece is determined by their comprehensive influence [76, 93]. The reciprocal effects of different surface integrity factors on fatigue performance were analyzed and summarized in Figure 10.

First, based on the effects of poor surface topography and compressive residual stress on fatigue crack initiation and propagation process, concluding that their effects on fatigue performance inhibit each other is easy. The poor surface topography (i.e., the large surface roughness, local defects and inclusions) could induce stress concentration and accelerate fatigue crack initiation [21, 71]. Stress concentration can enlarge the local loading on the workpiece severely, which may cause the local stress to reach or even exceed the material yield strength. Once the summation of residual stress and applied stress reached or exceeded the material yield strength, serious residual stress relaxation would occur [99, 100]. Therefore, the severe stress concentration induced by poor surface topography could dilute the effect of compressive residual stress on fatigue performance by inducing residual stress relaxation.

In addition, Yao et al. [127] found that the poor surface topography could cause early unstable fracture and reduce the area ratio of the fatigue propagation zone. Nevertheless, many researchers suggested that the compressive residual stress mainly inhibit the crack propagation process to improve fatigue strength [8, 11, 49, 88, 89]. Therefore, the reduced fatigue propagation zone caused by poor surface topography could restrain the effect of compressive residual stress on inhibiting crack propagation and thus dilute the effect of compressive residual stress on fatigue performance.

In return, the crack tip closing [8] and the subsurface fatigue crack initiation [75, 84, 90, 91] induced by compressive residual stress could restrain the negative effect of poor surface topography on fatigue crack initiation.

Second, the reciprocal effect of poor surface topography and work hardening on fatigue performance was two-faced. On the one hand, based on the results above [25, 45, 46, 49], the poor surface topography mainly accelerates the fatigue crack nucleation, and the severe work hardening mainly accelerates the fatigue crack propagation. Therefore, their effects on fatigue performance can mutually combine to magnify each other. On the other hand, the increased yield strength induced by work hardening could inhibit the initiation of fatigue cracks [19, 35], which runs counter to the effect of poor surface topography and thus restrain the effect of poor surface topography on fatigue performance.

Finally, the effect of work hardening and compressive residual stress on fatigue performance can interact with each other as well. The increased yield strength induced by work hardening can reduce the residual stress relaxation and thus reinforce the effect of compressive residual stress on fatigue performance. Sidhom et al. [37] demonstrated the interdependence between work hardening modification and residual stress redistribution under cyclic loading by experimental and numerical approaches, which suggested that the higher the near surface work hardening was, the more stable the initial residual stress will be. Nevertheless, the work-hardening induced high brittleness can accelerate the fatigue crack propagation [49], while the compressive residual

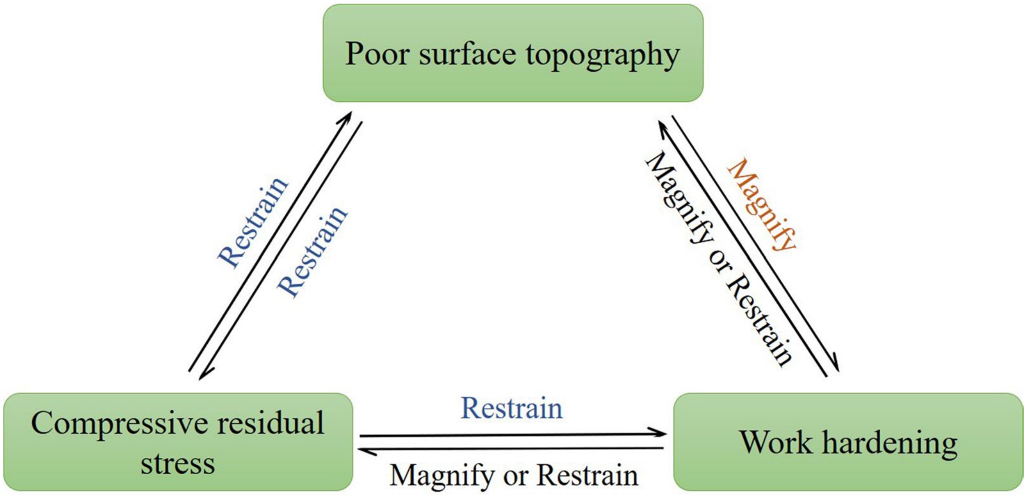

Figure 10 Reciprocal effects of different surface integrity factors on fatigue performance

stress can inhibit crack propagation [8, 49]. Therefore, the effects of work hardening and compressive residual stress may restrain mutually.

The complicated reciprocal effects of different surface integrity factors on fatigue performance increased the difficulty of revealing the influence mechanism of surface integrity on fatigue performance and in establishing the accurate prediction model of fatigue limit. A better way or model to study and characterize the effect of surface integrity on fatigue performance is crucial.

7 Conclusions

This paper summarized the current state-of-the-art studies on the effects of machined surface integrity, including the surface topography, residual stress, work hardening, and metallurgical structure changes on workpiece fatigue performance. The reciprocal effects of these factors on material fatigue performance were also discussed. Based on the discussion above, the main conclusions were summarized as follows. The limitations in existing studies and the future directions in anti-fatigue manufacturing field were proposed.

(1) The fatigue performance of machined workpiece was determined comprehensively by the surface topography (including the surface roughness, local defects and inclusions), residual stress, work hardening, and metallurgical structure changes. However, the complicated reciprocal effects of these factors on fatigue performance and an effective prediction model of fatigue limit are crucial.

(2) The stress concentration factor (K_t) was a useful indicator to describe the effect of surface topography on fatigue performance to some extent. However, the existing models and methods for calculating K_t ignored the material properties and the critical value of defects and inclusions, which need to be improved further.

(3) Compressive residual stress is propitious to workpiece fatigue performance. However, the residual stress relaxation under the cycle loadings needs further studies to predict its effects more precisely.

(4) The effect of work hardening on fatigue performance was two-faced. The work hardening induced high yield strength could delay crack nucleation, but the increased brittleness could accelerate crack propagation. In addition, the effect of work hardening was closely related to the metallurgical structure changes. Finding the effective control mechanism and method of work hardening and metallurgical structure changes to enhance the fatigue performance of machined components is urgently needed.

(5) Complicated reciprocal effects were discussed among the surface integrity parameters. The effects of poor surface topography and compressive residual stress on fatigue performance inhibit each other. The reciprocal effect of poor surface topography and work hardening was two-faced (magnify or restrain each other). The compressive residual stress can restrain the effect of work hardening on fatigue performance, whereas the work hardening may magnify or restrain the effect of compressive residual stress.

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Authors' contributions
GL analyzed the effect of metallurgical structure changes and reciprocal effect of different factors on fatigue performance, and wrote the most part of the manuscript. CH guided the overall thoughts of the manuscript and analyzed

the effect of surface topography on fatigue performance. BZ analyzed the effect of residual stress on fatigue performance. WW and SS analyzed the effect of work hardening on fatigue performance. All authors read and approved the final manuscript.

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Competing Interests

The authors declare no competing financial interests.

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