

Fatigue life of machined components

A. Pramanik¹ · A. R. Dixit² · S. Chattopadhyaya² · M. S. Uddin³ · Yu Dong¹ ·
A. K. Basak⁴ · G. Littlefair⁵

Received: 19 July 2016 / Accepted: 22 December 2016 / Published online: 17 February 2017
© Shanghai University and Springer-Verlag Berlin Heidelberg 2017

Abstract A correlation between machining process and fatigue strength of machined components clearly exists. However, a complete picture of the knowledge on this is not readily available for practical applications. This study addresses this issue by investigating the effects of machining methods on fatigue life of commonly used materials, such as titanium alloys, steel, aluminium alloys and nickel alloys from previous literature. Effects of turning, milling, grinding and different non-conventional machining processes on fatigue strength of above-mentioned materials have been investigated in detail with correlated information. It is found that the effect of materials is not significant except steel in which phase change causes volume expansion, resulting in compressive/tensile residual stresses based on the amounts of white layers. It is very complex to identify the influence of surface roughness on the fatigue strength of machined components in the presence of residual stresses. The polishing process improves the surface roughness, but removes the surface layers that contain compressive residual stresses to decrease the fatigue strength of polished specimens. The

compressive and tensile residual stresses improve and reduce fatigue strength, respectively. Grinding process induces tensile residual stresses on the machined surfaces due to high temperature generation. On the other hand, milling and turning processes induce compressive residual stresses. High temperature non-conventional machining generates a network of micro-cracks on the surfaces in addition to tensile residual stresses to subsequently reduce fatigue strength of machined components. Embedded grits of abrasive water jet machining degrade the fatigue performance of components machined by this method.

Keywords Traditional machining · Non-traditional machining · Fatigue strength · Surface roughness · Residual stress · Phase change

1 Introduction

Materials under a fluctuating stress fail at a much lower stress level than those under the static fracture stress. This fact is particularly important when designing aerospace, automobile and biomedical components [1–3]. It is well known that the cracks due to fatigue usually start from free surfaces as it undergoes the maximum load and environmental effects [4, 5]. The fatigue performance of a component depends on the topography/integrity of the machined surfaces produced by different machining procedures. Thus the surfaces generated from diverse machining processes show a wide range of fatigue behaviours [6]. Therefore, machining induced residual stresses, microstructures, microhardness and notch-like surface irregularities affect the fatigue strength significantly [7, 8]. The high cycle fatigue strength is the main mechanical property that is affected by machining in which rougher

✉ A. Pramanik
alokesh.pramanik@curtin.edu.au

¹ Department of Mechanical Engineering, Curtin University, Bentley, WA 6102, Australia

² Department of Mechanical Engineering, Indian School of Mines, Dhanbad 826004, India

³ School of Engineering, University of South Australia, Mawson Lakes, SA 5095, Australia

⁴ Adelaide Microscopy, The University of Adelaide, Adelaide, SA, Australia

⁵ School of Engineering, Deakin University, Waurn Ponds, VIC, Australia

surfaces inspire the beginning of fatigue crack, especially for notch-sensitive materials [9]. The surface microstructure includes phases, plastic deformation, tears, voids, pits, burrs, cracks and hardness. The machined surfaces are work-hardened severely with micro cracks. This change in the surfaces depends on the harshness of the parameters used during a machining process [10]. The tensile residual stresses on the machined surfaces degrade the fatigue life [5, 11].

Cast or wrought processes produce a near net shape, but machining processes generate final details of products. Appropriate precautions must be taken during the machining of components to ensure expected roughness and integrity of the machined surfaces/subsurfaces as they affect the service life duration significantly. There are some studies on the fatigue behaviour of machined components, which show that a variety of materials and machining processes have different effects on fatigue strength. A clear understanding of these effects is not yet available though it is imperatively required to utilize machined components more efficiently. This paper investigates the contributions of machining parameters on the fatigue strength of various materials, such as titanium alloys, steels, aluminium alloys and nickel alloys in the previous work. This review is anticipated to bridge all the understandings obtained by various researchers and, scientifically and systematically analyse those to give a complete understanding of fatigue behaviour of machined components.

2 Titanium alloys

Titanium alloys are mainly used in high-tech applications because of their excellent properties, but with high processing cost [12, 13]. Therefore much research has been performed on this metal alloy material. The latest research has been dedicated to experimental investigations of the inherent basis of inconsistency in fatigue strengths of machined titanium alloys. A significant scatter in fatigue data is evident specifically due to metallurgical aspects [14].

2.1 Effect of turning

The S–N results of Ti-45Al-2Nb-0.8%TiB₂ turned at different feeds and speeds are given in Fig. 1. The scatter of the results for turned specimens is quite high at all stress levels, which becomes lower for polished specimens at higher stress levels. The fatigue life of turned specimens diminishes at higher stresses owing to corresponding cracks initiation. No clear trends of fatigue lives of specimens machined at speeds of 10 m/min and 25 m/min, feeds

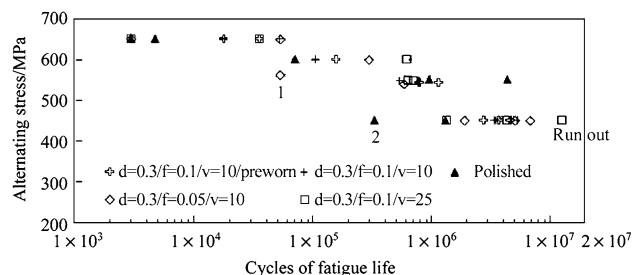


Fig. 1 Rotating bending fatigue life of Ti-45Al-2Nb-2Mn-0.8%TiB₂ [10]

of 0.1 mm/r and 0.05 mm/r, and depth of cut of 0.3 mm are noted [10].

According to Ref. [10], turned gamma alloys contain high compressive residual stresses in machined surfaces (around 600 MPa). The stresses in the longitudinal direction were smaller than those in the transverse direction. The surfaces generated from grinding also contain compressive residual stresses [15]. It is natural that the workpieces machined by worn tools have higher compressive residual stresses on the surfaces [16], which reduces the peak tensile stress and shows longer fatigue lives at the given stress when compared to the specimens machined at 10 m/min in speed, 0.1 mm/r in feed and 0.3 mm in depth of cut. However, Fig. 1 does not support the above. The specimens polished at 450 MPa and 650 MPa have lower fatigue life as opposed to turned specimens, as shown in Fig. 1. This indicates that the fatigue life of polished specimens is shorter due to little/no compressive residual stresses in the machined surfaces though polished specimens are free from cracks. Unfortunately, specimens polished at 550 MPa possess the highest average fatigue life. An approximate endurance limit of 350 MPa for all the specimens was calculated based on Fig. 1. A significant difference in endurance limit for different machining parameters was not manifested. A similar trend was noted for Inconel 718, which exhibited endurance limits of 420 MPa when gentle ground surfaces were compared with gentle and harsh turned surfaces [17].

2.2 Effect of grinding

Figure 2 shows flat S–N curves for high cycle four-point bending of Ti-45Al-2Nb-2Mn-0.8%TiB₂ processed at different conditions. The similar results are noted for electrical discharge machined [18] and turned specimens [10]. The fatigue strengths of fine-ground workpieces are inferior to those of polished and rough-ground counterparts. It seems that tensile residual stresses take place in the machined surfaces, which might be due to excessive heating from the grinding process, as previously mentioned by Koster and Field [19] when grinding an α/β titanium

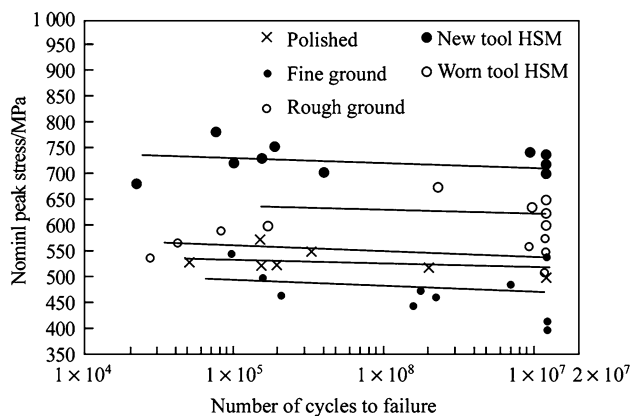


Fig. 2 High cycle, four-point bending, S–N curves for machined and polished Ti-45Al-2Nb-2Mn-0.8%TiB₂ surfaces [1]

alloy. Characteristically, rough grinding generates higher tensile residual stresses than those of finish-grinding, thus leading to higher fatigue life of a finished ground [1]. Metallographic sections show no microstructural differences between polished and fine-ground surfaces. Distorted lamellae are observed in the rough-ground and high speed milled surfaces.

2.3 Effect of milling

Distorted lamellae were also seen in the high speed milled surfaces where the depth of the distorted lamellae was up to 20 μm. Cracks were observed in single-point-turned specimens [10] and in the samples after high speed milling (HSM) with worn tools, depicted in Fig. 3. High speed milled specimens show significantly higher fatigue strength due to the increase of subsurface microhardness and deformation. The workpieces machined at the high speed have much harder and plastically deformed subsurfaces

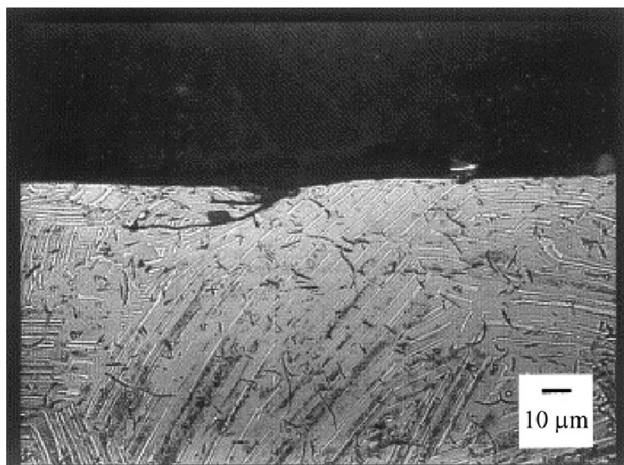


Fig. 3 Cracks in the machined surfaces produced by HSM with a worn tool [1]

compared to ground and polished surfaces. Such plastic deformation associated with the ploughing by the cutting tool, causes compressive residual stresses. The cracks in the machined surface generated from HSM by worn tools explain lower run-out values [1].

In general, trans-lamellar fracture and inter-lamellar failure are the predominant micro-mechanism of failure [18]. The deformation of the surfaces during HSM may limit the crack growth from the lamellae borders, which restricts failure among lamellar and increases the fatigue strength of the components [1]. Roughness of the machined surfaces significantly affects the fatigue strength of components. The surface waves act as stress concentrators and initiates cracks [10]. However, the increase of fatigue strength was not obvious with the increase in surface finish due to the presence of residual stresses in the machined surfaces [1].

All titanium alloy specimens experience brittle fracture, as shown in Fig. 4 [1], which displays inter-lamellar, intra-lamellar and trans-lamellar fracture. Inter-lamellar and intra-lamellar transmissions yield fracture surfaces parallel to lamellar boundaries and trans-lamellar spreads nearly in the normal direction to the lamellar boundaries. Fracture commencement locations on the surface are difficult to assess. It appears that untimely fracture at points 1 and 2 in Fig. 1 might be associated with the surface imperfection or favourable alignment of neighbouring groups to facilitate interfacial fractures.

2.4 Effect of electrical discharge machining (EDM)

EDM process of Ti-6Al-4V produces lower surface roughness ($R_a = 0.2 \mu\text{m}$) and fatigue limits (200 MPa) [20]. However, the aggressive EDM processing parameters on bi-modal, annealed Ti-6Al-4V result in higher

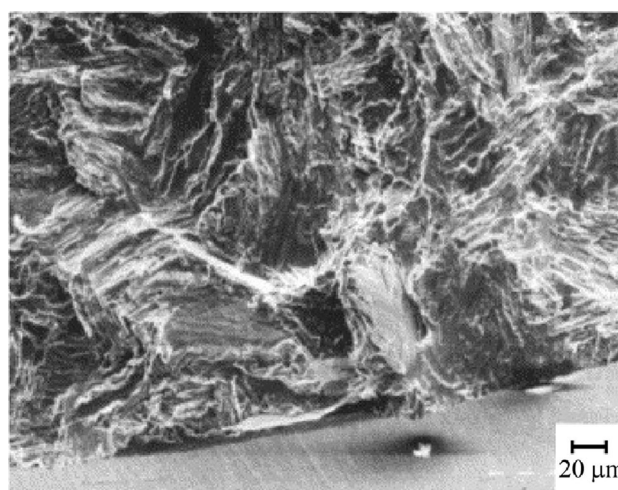


Fig. 4 Ti-45Al-2Nb-2Mn-0.8%TiB₂ fatigue fracture surfaces [10]

surface roughness ($R_a = 11.6 \mu\text{m}$ and $R_{\text{max}} = 78 \mu\text{m}$) [21]. Rotating-beam tests demonstrate severely reduced fatigue strength due to the EDM process. The fatigue limit was less than 100 MPa for the specimens after EDM while that of electro-polished specimens produced a fatigue limit of approximately 550 MPa. This degradation was attributed to both a high population of micro-cracks and tensile residual stresses on the specimen surfaces produced by EDM. The electro-polished specimens were reported to have zero roughness. The endurance limit of bi-modal, EDM-processed specimens can be increased significantly by stress relieving at 500 °C [22]. Fatigue behaviour of EDM processed Ti-6Al-4V alloy consists of three types of microstructures namely, equiaxed, bi-modal and coarse lamellar, illustrated in Fig. 5. The S–N curves are shown for all three microstructures of titanium alloys after EDM is compared with electro-polishing. The fatigue behaviour of equiaxed and bi-modal microstructures after electro-polishing depends on the prior aging and the grain size [23]. The fatigue endurance limit of electro-polished equi-axed and bi-modal microstructures is equal. The fatigue strength of coarse lamellar structure is much poorer than that of equi-axed or bi-modal structures [24]. Figure 5b compares the fatigue performances of different microstructures processed by EDM, which shows a significant decrease in the fatigue performance of all microstructures after EDM. This is due to the notch sensitivity of titanium alloys, perhaps brittle surface layers and micro-cracks generated from the EDM. It is also shown that the effect of EDM processed microstructure on the high cycle fatigue strength is small. The commencement of cracks in rotating bending is generally controlled by the quality and topography of machined surfaces [25]. Better fatigue performance at high stress amplitudes is noted for the coarse lamellar structure due to slower crack propagation, which is caused by the deviations of the crack tip from the average transmission plane. The longer high cycle

fatigue life of bi-modal structure at low stresses proposes a longer micro-crack spreading phase [21].

2.5 Comparison of different non-traditional machining processes

Figure 6 shows the S–N curves for Ti-6Al-4V samples manufactured by different processes. The curves are comparatively straight when the number of cycles to failure varies significantly with similar amounts of stresses. The specimens manufactured by turning have the highest run-out strength of 475 MPa. Electro-chemical machined (ECM) samples have a marginally lower run-out strength of 440 MPa, while the electro-discharge textured sample by low energy parameters (EDT-L) and those by high energy parameters (EDT-H) have considerably lower values of 357 MPa and 225 MPa, respectively [23].

The existence of cracks that propagate into the bulk of the material is the main cause of low fatigue strength of specimens produced by the EDT, as shown in Fig. 7a. Very high temperature is produced in the EDT process (12 000 °C), which melts the metal during machining. A molten pool of metal solidifies at the workpiece surface after machining. This solidification process is very rapid, which generates tensile residual stresses and micro-cracks on the machined surfaces. The cracks were not constrained to the recast white layers, but prolonged into the material beneath [26]. These cracks tended to follow lamellae and colony boundaries without much resistance to the spread of fatigue cracks [27]. Comparatively rough surfaces ($R_a = 1.43 \mu\text{m}$) of ECM specimens were generated by a discerning etching of distinct lamellae within individual colonies, as shown in Fig. 7b. Apparently there were no cracks on the surfaces generated by ECM. However, the selectively etched lamellae act as stress concentration points and the adherence of distinct lamellae offers the minor resistance to the crack commencement. On the other

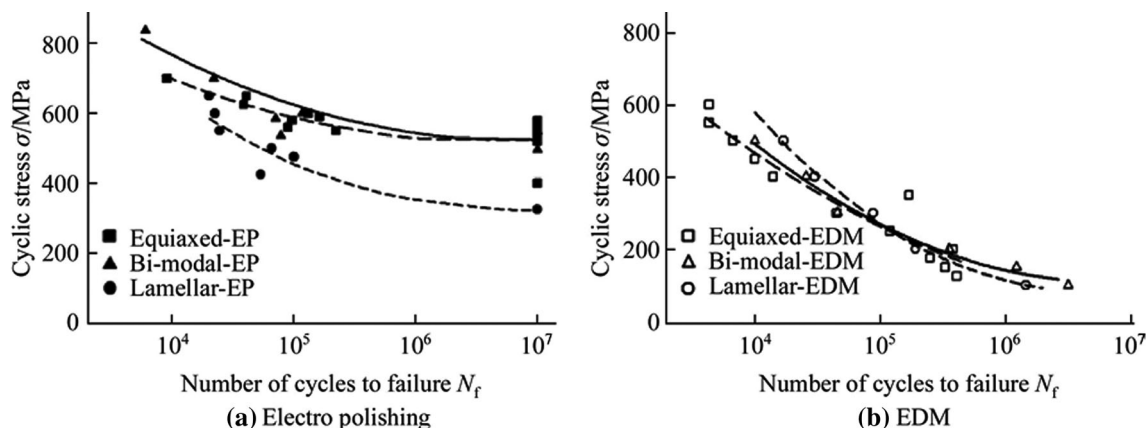


Fig. 5 S–N curves of Ti-6Al-4V alloy with different microstructures after **a** electro-polishing and **b** EDM [23]

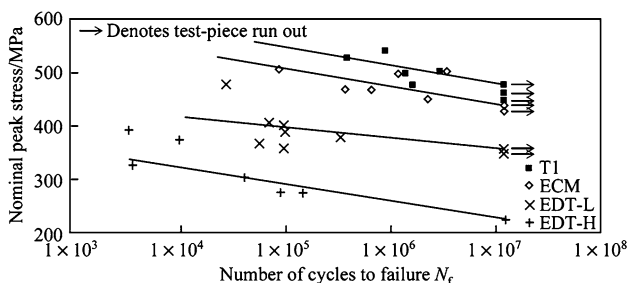


Fig. 6 S–N curves for turned, ECM and EDT specimens [26]

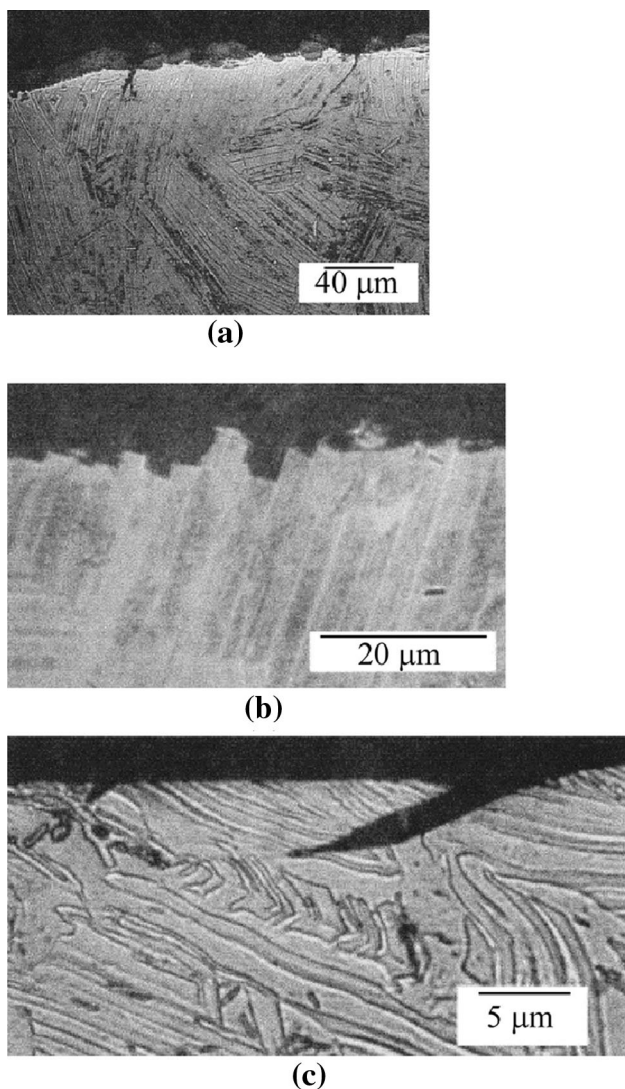


Fig. 7 **a** Crack morphology of EDT specimens; **b** selective etching of the workpiece produced by ECM; **c** crack morphology of turned specimens [26]

hand, there are small shallow cracks (<5 μm deep) in the turned specimens, as exhibited in Fig. 7c, and these cracks do not spread during fatigue tests. Crack origination on the specimens produced by turning occurred due to the failure

of inter-lamellar plate within lamellae colonies that were oriented at a certain angle to the applied load. In this case, the crack propagated at surfaces and internal sites. A longer fatigue life was demonstrated by the turned specimens as it required more cycles to propagate cracks through the compressive residual stress layers [26].

The fabrication of metallic components using EDM generally creates residual tensile stresses within the surface layers, because it shrinks during cooling while being restrained by the adjacent cooler interior material. This effect is exacerbated by the low thermal conductivity of titanium. Tensile residual stresses in Ti-6Al-4V plate machined by micro-EDM can be as high as 350 MPa at depths of up to 12 μm [28]. In addition, it can be 250 MPa at depths of up to approximately 40 μm in titanium-alloy bars [29]. These levels of measured residual stresses are a significant fraction of the fatigue limit, which directly contribute to the reduction of the fatigue strength.

It is well-known that surface finish can influence the fatigue life of materials quite strongly. Influential parameters available in wire EDM of Ti-6Al-4V include electrode materials, electrical discharge time and current. These parameters affect the surface roughness and recast-layer thickness, which ultimately contributes to the fatigue performance [30]. The average recast-layer thickness could be reduced from nearly 100 μm to 5 μm by reducing both the pulse duration and current with the aid of aluminum wire instead of graphite or copper. The corresponding reduction of surface roughness was from almost 10 μm to 1 μm. The surface micro-cracks density could decrease with the increase in pulse current and decrease in pulse duration [31]. Substantial improvement in the quality of EDM surfaces can be achieved using “minimum damage generator technology” [32], where pulse waveform and frequency vary in addition to electrical current. Average surface roughness below 0.5 μm and negligible thickness of recast layer can be achieved for both Inconel 718 and Ti-6Al-4V specimens using this technology [22]. During high-cycle fatigue of many metals, the majority of cyclic lifetime (up to 90%) is consumed during the creation of an initial flaw, or sub-critical crack [33]. The presence of micro-cracks in brittle, thermally-processed surface layers—typical of EDM processing—creates ripe for pre-existing flaws to exist [34]. In such cases, it is expected that the lifetime of parts placed into cyclic stress conditions can be abbreviated, relative to nominally similar components in absence of such defects.

Tensile fatigue strength of specimens turned, ground with “low stress” and mechanically polished, and electro-polished varies by more than one order of magnitude at a given stress level. This suggests that a “short-life” mode of fatigue crack initiation evolves at near-surface alpha grains that are suppressed by polishing process [35]. Table 1

Table 1 Effect of machining on fatigue strength of titanium alloys

Reference and test type	Machining process	Conclusion
Ref. [10] Rotary bending fatigue test	Turned at speeds of 10 m/min and 25 m/min, feeds of 0.1 mm/r and 0.05 mm/r and depth of cut of 0.3 mm are noted	The scatter of the results for the turned specimens is quite high at all stress levels. The fatigue life of turned specimens diminishes at higher stresses because of the cracks initiation at higher stresses. No clear trends of the fatigue lives of samples are noted
Ref. [1] Four-point bend (tension-tension) fatigue test	Ground specimens were machined on a surface grinding unit with conventional SiC abrasive wheels. Milled specimens were produced by four-flute, coated, cemented tungsten carbide ball nose end tools	A reduction in fatigue life was noted due to finish grinding compared to that of rough grinding and polishing. The fatigue strength was substantially increased by milling in spite of surface cracks and deformed lamella. It was likely that this was due to compressive residual stresses near the surface and/or deformation of the lamellae restricting crack growth
Ref. [23] Rotary bending fatigue test	EDM with graphite electrodes and using hydrocarbon oil as dielectric liquid. High peak current of 29 A was employed. The samples were electrolytically polished at $-20\text{ }^{\circ}\text{C}$ and removed $100\text{ }\mu\text{m}$ from the surfaces after machining	Very low fatigue endurance of electro-eroded (EDM processed) specimens. This was caused by tensile stresses in near-surface regions, pre-existing micro-cracks and high surface roughness. The fatigue limit was less than 100 MPa for the samples after EDM while that of electro-polished specimens produced a fatigue limit of approximately 550 MPa. Both transcrystalline and atypical faceted fractures were initiated
Ref. [22] Tension-tension fatigue test where cyclic loading used a sinusoidal waveform at 10 Hz	Specimens produced by EDM were treated by (i) bead blasting using $50\text{ }\mu\text{m}$ silica beads from a 2.4 mm in diameter nozzle at 400 kPa, (ii) electrochemically polished using nitric acid based solution to remove $20\text{ }\mu\text{m}$ layer from all surfaces, (iii) electrochemically polished and thermal stress-relieved at $594\text{ }^{\circ}\text{C}$ for 2h, and (iv) chemically milled using a nitric acid based solution to remove $10\text{--}20\text{ }\mu\text{m}$ from all surfaces	EDM process reduces fatigue strength by 15%–30% when compared to that machined conventionally. This strength degradation is attributed to the presence of stress-concentrating defects within the EDM recast layers. Specimens fabricated with the EDM process were shown to create the roughest surfaces. Post-processing with either electrochemical polishing or bead blasting was demonstrated to alleviate the deleterious effects of EDM, thereby restoring the intrinsic fatigue behaviour, as indicated by the crack initiation at interior locations
Ref. [26] Tension-tension fatigue test	The turned samples were made under operating conditions that caused the minimal surface damage. The ECM specimens were initially turned oversize and subsequently machined to remove $250\text{ }\mu\text{m}$ from the test surfaces. Two levels of EDT operating energy were selected, one using EDT-H to provide specimens with deep cracks and one using EDT-L to produce shallow cracks	The presence of cracks penetrating into the bulk of fatigue specimens, in combination with the presence of tensile residual stresses, resulted in the substantially reduced fatigue life of the EDT specimens compared to those that had been turned and ECMed. The lower life of EDT-H, as compared to EDT-L specimens, reflected the presence of deeper cracks and higher tensile residual stresses. It was likely that the higher fatigue life of turned specimens was due to the highly compressive residual stresses present in the machined surfaces

summarises the major studies on the effect of machining on fatigue strength of titanium alloys.

3 Stainless steel

Machining of steels alters the surface layers of work pieces, which produces surfaces that are harder/softer than those of bulk materials [36, 37].

3.1 Effect of turning

Thiele et al. [38] studied the influences of workpiece hardness on residual stresses of hardened AISI 52100 steel surface produced by finish hard turning. For the considered experimental conditions and cutting edge geometry, it was noted that the axial stress component for the workpiece with higher hardness was more compressive. The microstructural analysis reveals that three basic

microstructural patterns exist on the workpiece surface such as continuous white, intermittent white and dark layers. These layers are created by heating and successive cooling of machined surfaces during the machining process. The white layers are created by heating the samples above the α - γ phase transformation temperature and successive quick cooling during the cutting process. Dark layers are composed of over-tempered martensite with easy etching and are typically located beneath continuous white layers and, below and adjacent to intermittent white layers. The interior surfaces of the workpieces are tempered martensites. Surface residual stresses in the axial and hoop directions are associated with individual microstructural patterns. Specifically, compressive residual stresses in the hoop and axial directions are evident when the workpiece's surfaces contain continuous white layers [39]. The main cause of compressive residual stress formation in samples exhibiting continuous white layers to contribute volume expansion is phase transformation. During machining, the tempered martensite in the workpiece surface transforms to austenite. Rapid cooling causes the generation of an untempered martensite, which attempts to inflate. The interior workpiece material places the surface layers in compressive residual stresses. Samples that show dark layers on the workpiece surfaces normally correlate with tensile residual stresses in the hoop and axial directions. By considering the thermal expansion and subsequent cooling of the workpiece surfaces, constrained by the workpiece interior, the correlation between formation of dark layers and tensile residual stress could be explained. Thermal gradient produced by the cutting process causes the surface layers to expand more than inner layers, eventually leading to plastic deformation. Upon cooling, the surface layers attempt to shrink to a length smaller than the interior layers, and are placed in residual tension to maintain equilibrium. Finally, surface layers consisting of intermittent white layers may undergo tensile or compressive stresses depending on the amount of existing white layers. Large amounts of intermittent white layers correlate with compressive residual stress in the hoop and axial directions or vice versa [38].

Javidi et al. [5] investigated the correlation between turning parameters, surface integrity and fatigue properties of 0.34% carbon steel type 34CrNiMo6 (quenched and tempered). A larger feed gives a quicker machining but a higher surface roughness. The larger nose radius generates lower surface roughness but an extremely long nose radius may induce vibration affinities, unacceptable chip breaking and higher tool wear owing to inadequate cutting edge engagement. An increase in the nose radius of the insert reduces the compressive residual stresses. Higher compressive residual stress induces longer fatigue life and the influence of residual stresses on fatigue behaviour

outperforms that of surface roughness [5, 40]. Figure 8 shows the influence of nose radius on S-N curve for 34CrNiMo6 steel. It clearly indicates that the fatigue strength of the components produced by turning increases with the decrease in nose radius.

Lower feed causes the surface residual stress to swing towards the compression, which influences the fatigue behaviour significantly. The trend towards higher tensile stresses due to the increase of temperature during machining at higher feed [41]. A crack that starts beneath the machined surfaces might propagate until a compressive stress region where the crack will be retarded till the relaxation of stresses. The higher feed generates a tensile residual stress zone, and therefore the crack propagates until rupture. If the probability to initiate cracks from the surface increases, the crack initiation will occur first in samples produced by small feed, which then propagates till the compressive stress zone. The samples with higher compressive residual stresses on the surfaces require a longer time to initiate and spread a crack from the surfaces [42]. The cracks with depth of up to 5 μm in the surfaces produced by turning can be compensated for by compressive residual stresses, which further decreases the applied tensile stress. In a similar manner, turning becomes more favourable than grinding with respect to the fatigue behaviour of hardened bearing steel [39]. HSM with the proper machining conditions might increase fatigue strength [1]. This process causes higher plastic deformation/strain hardening and lower temperatures, which generates compressive residual stresses at/adjacent to the machined surfaces [7].

The effect of the cutting edge geometry of turning tools on the fatigue life was investigated by Sasahara [43]. The residual stresses in the hoop direction in the surface machined by chamfered cutting edge were more

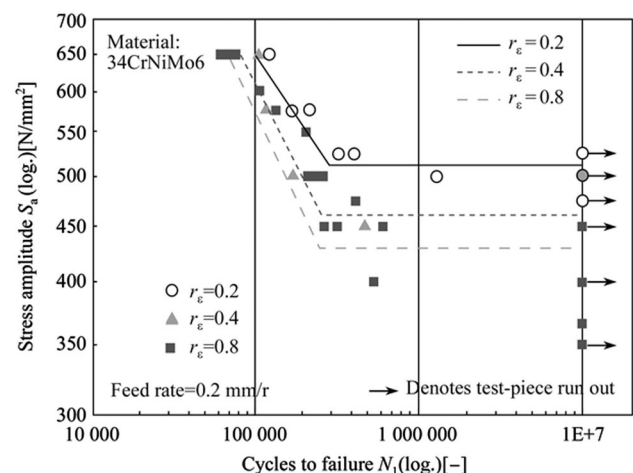


Fig. 8 S-N curves of samples turned with inserts of different nose radius [5]

compressive than those of the machined surfaces produced by sharp cutting edges. However, the variation of hoop residual stresses is minor between surfaces machined by the chamfered and sharp edge tools. The smaller corner radius of chamfered tools increases the hardness of machined surfaces, which indicates that the plastic deformation of the machined surfaces increases with decreasing the corner radius. This is another reason of the wide variation for the fatigue life of the specimens with identical surface roughness. Effects of hardness and axial residual stresses on fatigue life at different edge preparation and cutting conditions are given in Fig. 9. The fatigue life nearby point A is short where the tensile residual stresses and lower surface hardness are noted. Conversely, the fatigue life nearby point B is longer where the axial residual stress is close to neutral and the hardness is larger than 290 HV. Higher compressive residual stresses and hardness that are identical to those of point A are noted around the point C where fatigue life is higher than that around point A. Therefore, high compressive residual stresses and high surface hardness are necessary for longer fatigue life, as shown in the region D in Fig. 9 [43].

All normal residual stress components in the finish hard turned through-hardened AISI 52100 steel become more compressive with rise of cutting edge hone at a constant feed rate. The stresses in the radial direction are generally smaller than the other stress components [38]. The principal stresses produced by each edge preparation are somewhat different, despite the similarities in the normal stress components [38]. The fatigue life increases with the increase of surface hardness due to the increase of the yield strengths of surface layers by the work hardening. The work hardening and the residual stress depend on each

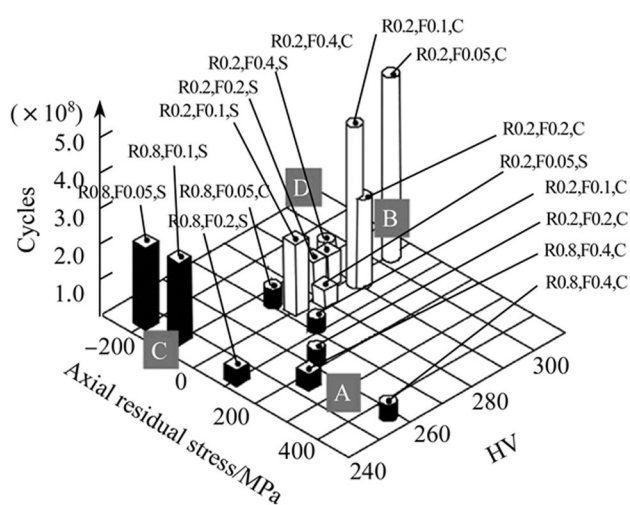


Fig. 9 Effects of axial residual stresses and hardness on fatigue life at different edge preparation and cutting conditions (where R and F represent the roughness and the feed rate, respectively, S indicates sharp edges and C means chamfered edges) [43]

other through the machining processes. The distribution profiles of residual stresses and hardness also influence the fatigue life. The residual stresses and the surface hardness can be regulated through the proper selection of feed rate, corner radius and cutting edge radius during a machining process. The residual stress becomes nearly zero and the surface hardness hardly changes when the corner radius of cutting tool is small. Machining by cutting tools with a smaller corner radius at the low feed rate increases the fatigue life of the machined components. Therefore, the correlation between residual stresses and the surface hardness might be evaluated to identify optimum machining parameters [40, 43].

The increase of cutting edge radius reduces the real rake angle on the way to the negative values [40]. Hence, the influence of larger edge radius is comparable to a negative rake angle (i.e., inducing compressive residual stresses underneath the machined surfaces). Abhang and Hameedullah [44] argued that the contact area for heat dissipation increased as the radius of tool nose increased, which generated lower tensile residual stresses on the machined surfaces as the local temperature along the cutting edge decreased. However, with the increase in contact area, the friction between tool and workpiece is enhanced as well, which increases the heat generation owing to the friction and contributes to higher tensile residual stresses. Simultaneously, lower tool/part pressure per area decreases plastic deformation as the contact area increases. Hence, the increase of tool nose radius infers increased temperatures due to the friction and lower plastic deformation, thus resulting in more tensile surface residual stresses [40].

Garcia and Moisan [45] concluded that the higher cutting speed tended to induce tensile residual stresses, but the tendency is not certain as to the peak width for AISI 4340 steel. Increased cutting speed enhances the local temperature close to the cutting edge, which promotes tensile residual stresses (thermal stresses) on the machined surfaces. If the generated temperature is higher at the surfaces and the depth of heat infiltration is lower, the martensite transformation in quenching is likely to occur, which facilitates the generation of the compressive residual stresses.

Rech and Moisan [46] and M'Saoubi et al. [47] used coated tools with stable cutting parameters (i.e., reduced cutting forces and better chip formation), which generated less tensile residual stresses because of better tribological behaviour (i.e., lower friction and lower heat generation during machining). However, the coating of inferior thermal conductivity hinders the machining heat from degrading the cutting tool and extends the tool life, but tends to transmit higher amounts of heat to the workpieces. This heating of the workpieces could be accounted for tensile residual stresses when using coated tools [45].

Tool wear is unavoidable during machining process, which makes cutting tools blunt. Thus the wear of the tool increases the heat generation and thus the increase of residual stresses. Dry machining increases the heat generation in the contact areas [48]. Measured residual stresses on the surfaces dry machined with worn tools may exceed the yield strength of SAE 4340 steel. This is due to severe plastic deformation and very high strain hardening of the machined surfaces. In the same fashion, heating from the friction might change the phase and generate residual stresses. Hardening of machined surface layers is influenced by elastic and plastic behaviour of materials, thermal expansion coefficient and similar physical properties [48]. The machining conditions influence the endurance limits of the threaded SAE 4340 steel over a wide range. The most noteworthy thread machining factor to influence the fatigue behaviour is tool wear, which is followed by the machining speed. However, the radial feed and thread cutting method are less influential. Residual stresses and strain hardening are needed to be considered for the design purposes that depend on the material and machining parameters [48].

The residual stresses on the machined surfaces rest on the materials being machined and on the cutting conditions [49]. Akyildiz and Livatvali [50] demonstrated that the machining conditions such as cutting speed, feed rate, and tool nose radius had great effect on the fatigue behaviour and surface quality of machined components [51, 52]. A complete knowledge on the influence of surface topography on the fatigue behaviour can only be obtained by investigating residual stress-free specimens and specimens where no phase changes occur. Unluckily, stress relieving treatments after machining processes alters the metallurgical state on the machined surface. Mantle and Aspinwall [10] studied the fatigue behaviour of stress free En19 steel (equivalent to AISI 4140) and found that comparatively low surface roughness (R_a 0.5–1.4 μm , R_t 7–14 μm) generated by modest grinding decreases the fatigue life compare to that of polished specimens where the surface roughness (R_a 0.1–0.3 μm , R_t 3–5 μm) is further low. The surfaces produced by grinding show higher fatigue strength than that of milled surfaces with identical surface finish (R_a , R_t). This resulted from the rounded feed marks generated by milling, which initiated premature cracks in the normal direction to the axis of samples. It was suggested that the roughness parameters such as R_t and R_z , were more suitable indicators of fatigue behaviour than R_a as they revealed the “worst” flaws existing on the machined surfaces.

3.2 Effect of grinding

The fatigue strengths from tension-tension tests of through-hardened AISI 52100 steel (60–62 HRC) machined by

different processes are given in Fig. 10 [53] with various surfaces of specimens clearly shown. Those are: (i) hard turned surfaces with continuous white layers (HTWL), (ii) hard turned surfaces with no white layers (HTnoWL), (iii) ground surfaces (G), (iv) hard turned surfaces (uninterrupted white layer) with super finish (HTSF), and (v) ground surfaces with super finish (GSF). The hard turned specimens showed better performance in all cases when compared with ground counterparts. The average fatigue life of HTWL specimens is 56 867 cycles as opposed to 27 360 cycles for the G specimens based on a traditional assessment. In reality, the poorest HTWL specimens have a fatigue life of 16 106 cycles, which goes beyond the average life of G specimens when the outlier is removed. The average value for the HTnoWL surfaces is similar to that of G specimens (24 657 versus 27 360 cycles) even in the absence of white layer. In the same manner, the average fatigue life of the HTSF specimens (323 897 cycles) appears to be far higher than that of GSF counterparts (19 427). The discrepancy in the fatigue behaviour is higher and such distribution is characteristic of high cycle fatigue testing. The harsh manufacturing parameters and discrepancies in tooling are two additional sources of this variation [53].

It is well accepted that the increase of compressive residual stresses substantially increases the fatigue life with such a relation that does not exist between surface finish and fatigue life. This indicates that the most significant dissimilarity between the surface integrity of specimens is the dissimilarity in the residual stress profiles. In the absence of obvious surface defects, the fatigue performance of the specimens is ascribed to residual stress profiles, in which the fatigue life increases with the increase in compressive residual stress. This tendency is expected between the HTnoWL and G specimens along with the HTSF and GSF counterparts. Nevertheless, the fatigue behaviour of HTWL specimens indicates that the existence of white layers does not change this tendency. This shows that the influence of the hard turning method on the fatigue behaviour of specimens is determined mainly by the

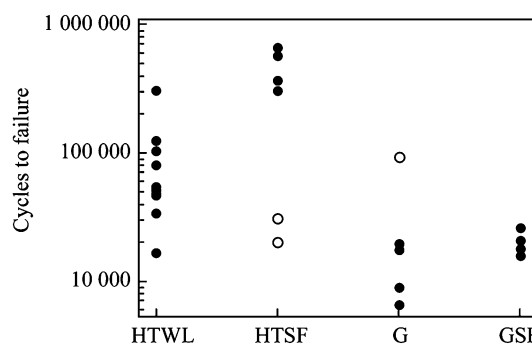


Fig. 10 Axial high cycle fatigue life results [53]

subsequent profiles of residual stresses [53]. Figure 11 plots the effect of the surface residual stresses in the axial direction on the average fatigue life. The figure demonstrates that the fatigue life of machined specimens is approximately linearly proportional to the compressive residual stresses of machined surfaces.

Rolling contact fatigue tests were performed to study the consequence of precision hard turning and grinding on the fatigue life by Matsumoto et al. [54]. The change of the surface microstructures after grinding along with hard turning during the process of making bearings with optimum conditions was not manifested. The most important dissimilarity between ground bearings and hard turned bearings after super finishing was the residual stress profile and depth of compressive residual stresses. Figure 12 compares the residual stress profile in the ground and then super finished surfaces to that in the hard turned and super finished surfaces. After grinding and super finishing, a higher compressive residual stress is induced near the surfaces, which is yet reduced sharply as the distance increases along the depth from the machined surfaces. In contrast, the residual stresses extend to higher depth from the machined surfaces after hard turning and super finishing. Matsumoto et al. [54] reported significant local plastic deformation around micro-cracks during fatigue tests. A clear relation between the depths at which butterflies (this region has the appearance of butterfly wings when viewed in cross sections) were noted and the fatigue life was distinguished, namely the deeper the butterflies, the longer the fatigue life. Therefore, deeper compressive residual stress generated by hard turning is advantageous [54].

The basic dissimilarities in the integrity of hard turned and ground surfaces and the successive influence on rolling contact fatigue behaviour were studied by Hashimoto et al. [55]. It was reported that the turning process with a smaller

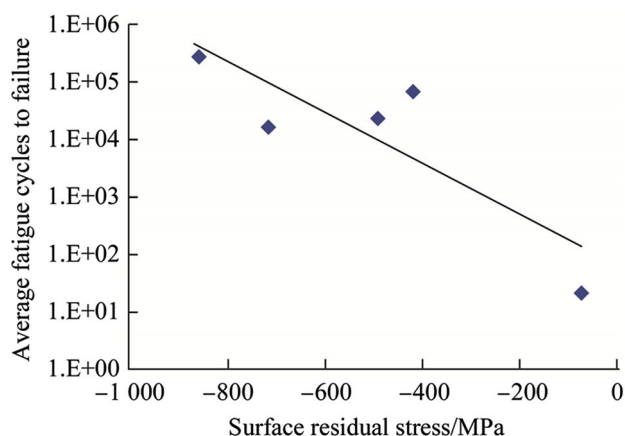


Fig. 11 Fatigue life vs. surface residual stress in the axial direction [53]

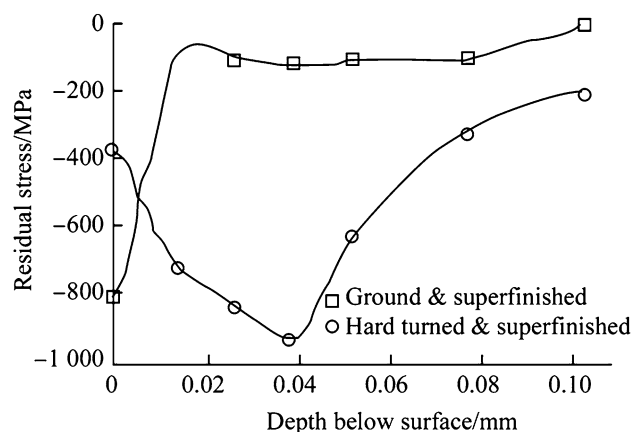


Fig. 12 Residual stresses along the depth of machined surfaces for different machining processes [54]

depth of cut and feed rate produced better ($\approx 30\%$) surface roughness than that of ground surface. Turned and ground surfaces are not thermally damaged, while grinding temperature has a much deeper excursion on the subsurfaces. It is evidently shown that the subsurfaces have two different zones categorised by a strain hardened zone in near surfaces and a thermally affected zone in the subsurfaces (not softened enough as compared to bulk hardness). White layers do not belong to the strain hardened zone. It is not darker than the bulk material and the thermally affected zone encountered in hard turning, as shown in Fig. 13. The dissimilarity of the two zones is just ascribed to their different resistance to etching due to the variation in grain deformation and size [55].

The variation of hardness at different depths may be influenced by different interactions between material phases and indenters. The fundamental mechanism for the harder ground surfaces/subsurfaces is most likely due to the size effect induced by the very high strain gradient during the grinding process. The lower down feed in grinding incurs very high strain gradient on near surfaces, however comparatively high depth of cut in turning may significantly decrease the size effect. The super finished turned surfaces may have 100% more fatigue life than those of G specimens with similar surface roughness. The facts that contribute to the inconsistency in fatigue behaviour are the distinct surface structures and properties generated in the processes [55]. According to the results of different studies, it can be concluded that the main dissimilarity between hard turning and grinding is that hard turning may induce deeper “surface” compressive residual stresses despite the provision of similar or better surface finish, form and accuracy. Thus, the dissimilar features of residual stresses induced by hard turning and grinding influence the fatigue behaviour of machined components in rolling contact [56].

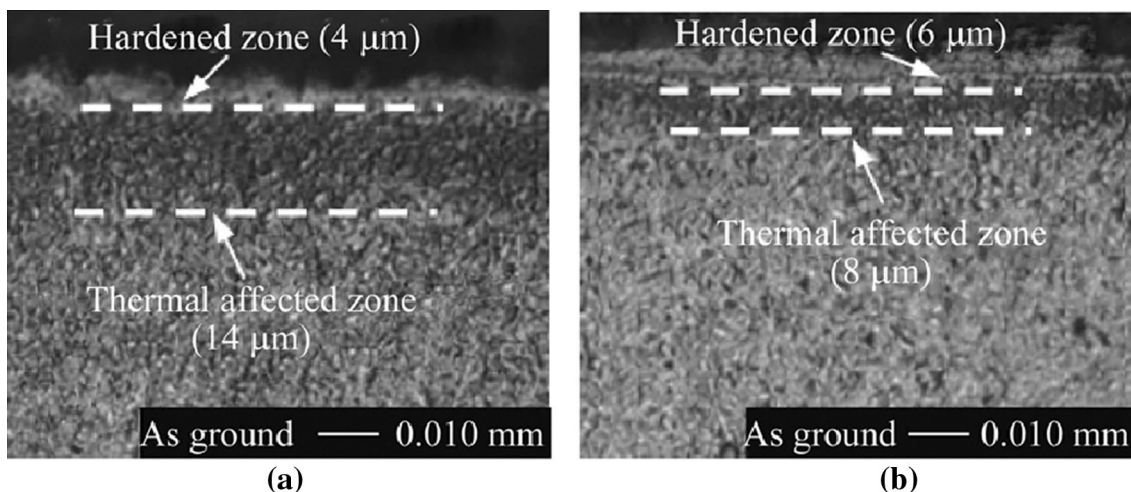


Fig. 13 Hard turned and ground surfaces [55]

3.3 Effect of milling

The effects of grinding and fly cutting (single point milling) methods on the fatigue behaviour of hardened AISI 4340 steel and their relation to surface integrity were studied by Matsumoto et al. [54, 57]. It was noted that the residual stresses produced by the milling process were mostly compressive. The compressive stresses are well known to improve fatigue strength in some cases. Three residual stress distributions on the machined surfaces measured parallel to the machining direction are shown in Fig. 14. The specimens were produced by grinding in the direction of the length of the specimen, fly cutting with feeding in the direction perpendicular to the length of the specimen, and fly cutting with feeding in the direction of the length of the specimen. All specimens carried compressive residual stresses except the top layer of machined surfaces milled perpendicular to length. The residual stress distribution produced by grinding had a high peak compressive residual stress on the machined surfaces. The stress on ground surfaces was shallow with a very steep gradient, while as for the others it reached much deeper. It appears that the residual stresses produced by grinding lie in a very shallow depth and might not have a noticeable influence on the fatigue limit. Conversely, the higher and deeper compressive residual stresses on the fly cut surfaces increased the fatigue limit in this investigation. It should also be noted that the residual stresses in the deeper layers become a more important factor, when the nucleation of a crack starts from inclusions in the subsurfaces. The investigation on the cross sectional structures of three machined surfaces indicates that there is no distinct structural change on the machined surfaces. The measured roughness of the ground surfaces had the largest maximum height R_{max} and the lowest endurance limit of fatigue [57].

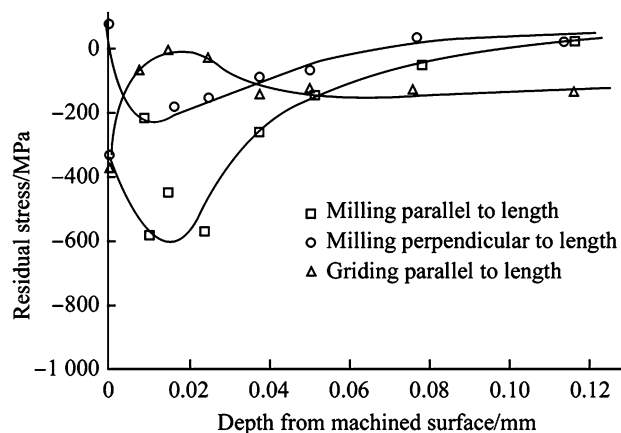


Fig. 14 Residual stresses measured in the direction of machining process [57]

There are three sources that are responsible for creating residual stresses on the machined surfaces. There is a martensitic phase transformation in the near surface structures, yielding surface or near surface elements due to thermal stresses caused by machining heat, and uneven plastic deformation of surface or subsurface elements. Under usual situations, when there is no excessive tool wear or abusive machining practice, very little martensitic formation is observed in the machined surface layer of hardened steel [58]. The existence of untempered martensite on the subsurfaces produces a compressive residual stress due to its larger volume. On the other hand, if the temperature rises in that the machining process does not reach the α - γ transformation temperature, further tempering can take place. If the further tempering takes place, more martensite is transformed into ferrite and cementite, thus volume reduction near the surfaces takes place. This result is a tensile residual stress on the surfaces. The

surface residual stresses on all machined surfaces are also compressive and if there is any tempering, its influence on the residual stresses could be minor.

3.4 Effect of non-conventional machining

EDM is a high energy density non-contact method [59], in which layered structures on the machined surfaces are generated due to melting and quick solidification of materials. The EDM of tool steels [60] creates three noticeable layers, (i) a “white layer” near the surface, with a dendritic structure resulting from the resolidification of metal melted during the EDM, (ii) a quenched layer with a martensitic structure just beneath the white layer, and (iii) a transition zone between the quenched layer and the base material. The EDM specimens demonstrate a higher surface hardening compared to conventionally machined (milled) specimens because of the near-surface phase changes and increased amounts of carbon. Under this circumstance, tensile stress is produced adjacent to the surfaces. A network of micro-cracks is also observed on the surfaces. This scatter of cracks changes significantly with any types of applied stresses. The cracks initiate, propagate freely and form an uninterrupted network, which leads to untimely failure of the specimens manufactured by the EDM compared to specimens manufactured by milling to generate better surface integrity and finish.

The metallurgical alterations of machined surfaces in the near-surface layers occur due to the sparks that extremely heat locally (up to 10 000 °C) in a very short time (6 μ s), and the successive cooling by the dielectric fluid and transfer of heat into the bulk material [61]. The thermal flux evaporates and melts the samples in order to generate craters of different sizes and shapes on the surfaces. Thus an irregular surface profile is generated from this process. The heating effect changes the machined surfaces, and the melted material goes through a “quenched”, then to a “tempered”, and to the unaffected bulk material. The changes on the machined surfaces are influenced by thermal behaviour of machined material and its capacity to harden [62]. The changes in hardness occur because of chemical and thermal effects [63] including the increase in carbon content and martensitic formation in the quenched layer. The disintegration of the dielectric causes diffusion of carbon results. The strains are caused by the thermal effects and phase transformation after the EDM induces tensile residual stresses on the machined surface. These stresses are partially relaxed at the surfaces because of the cracks produced from the EDM. The diffusion of hydrogen into the machined surfaces after the disintegration of the dielectric fluid causes near-surface embrittlement. Generally the cracks and tensile residual stress distribution on the

machined surfaces undermine fatigue behaviour of specimens produced by the EDM. Samples produced by the EDM and milling have similar fatigue properties because of the reduction of residual stresses from substantial cycling of strain hardening in low cycle fatigue tests. The spread of fatigue cracks in bulk materials is a key factor to regulate the fatigue behaviour of specimens produced by the EDM and milling in that the hardening embrittlement of changed layers from both methods is nearly undistinguishable. The residual stresses on the machined surfaces have greater influence on the high cycle fatigue properties [64], in which 35% reduction of endurance limit (at 10^6 cycles) is shown for specimens by the EDM treatment rather than milling treatment [60].

Figure 15 depicts the S–N curves from the axial fatigue tests on AISI 301 membranes produced using diverse manufacturing methods. The results are significantly scattered despite clear common trends. The membranes produced by stamping have a considerably better fatigue life than those produced from laser-cut and abrasive water-jet cut. The top stress to failure of stamped membranes is 15% higher than that of other processes for 1 million cycles of fatigue life. The influence of stress concentration is predominantly significant at the low cycle fatigue behaviour. At low cycle fatigue levels (i.e., where the stress is high), the effect of this stress concentration is particularly important as can be seen from the lower fatigue life of the laser-cut membranes as shown in Fig. 15a. Nonetheless, the high cycle fatigue properties of the membranes produced by LBM and AWJM are almost similar. Though the samples produced by AWJM and LBM (0°) show identical fatigue behaviour, the fatigue life of specimens from LBM (90°) is twice that of samples produced by LBM (0°) at identical stress. Figure 11b demonstrates the fatigue behaviour of stamped, EDM and EDM-shot peened membranes. The stress to failure for 5 million cycles and low cycle behaviour are almost identical for stamped and EDM-shot peened membranes. The membranes produced from the EDM have 20% lower fatigue strength for 5 million cycles than those of stamped membranes. Similarly, stamped membranes demonstrate higher fatigue strength than that of EDM at the low cycle [65].

It is proposed that micro-cracks on the machined surfaces with higher surface finish (e.g., polished surfaces), start from slip bands or at grain boundaries [8, 66, 67]. Nevertheless, micro-notches were generated through machining processes (e.g., grinding, turning and milling), concentrated stresses and localised plastic strain with the application of stresses. This happens in a discrete grain as a slip band that outlines the route of shear cracks [6]. Siebel [68] found that the highest depth (R_t) of surface profile generated from machining processes was the most important roughness factor to influence the fatigue behaviour of

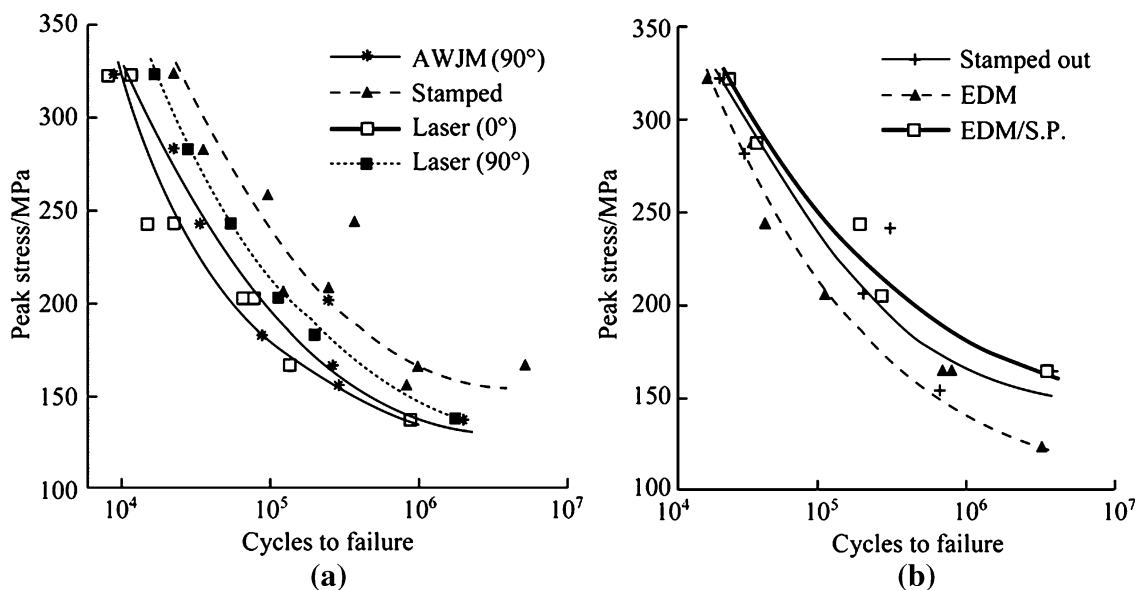


Fig. 15 S–N curves for AISI 301: **a** stamped, LBM and AWJM membranes and **b** stamped, EDM and EDM-SP membranes [65]

machined components. The decrease of fatigue endurance limit is proportional to $\log(R_t)$ when the maximum depth of the surface profile is larger than a certain critical groove depth. The critical groove depth is 1–2 μm for tempered steels and 4–6 μm for annealed steels, as demonstrated in Fig. 16. It is possible to eliminate the effect of surface finish on fatigue behaviour of machined components by inducing compressive residual stresses on the surface through post-machining mechanical treatment [7]. Table 2 summarises the major studies on the effect of machining on fatigue strength of stainless steel.

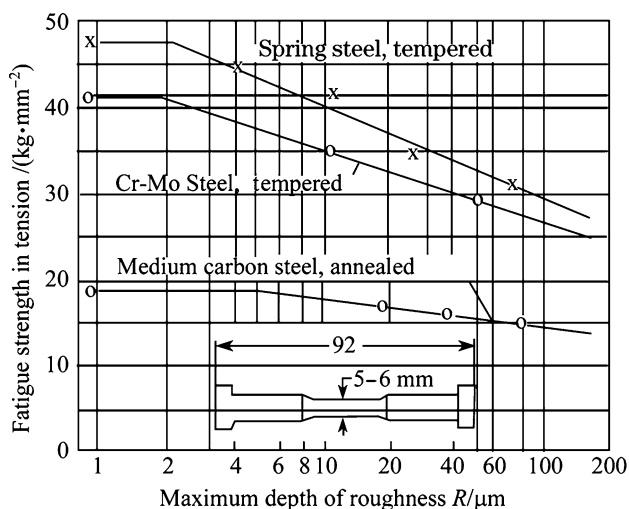


Fig. 16 Effect of maximum depth of surface profile on the fatigue strength of various steels in repeated tension [68]

4 Other materials

Bayoumi and Abdellatif [69] interrelated different surface roughness variables to the fatigue endurance limit of an aluminium alloy where R_a and R_q rather than spatial variable had a guiding effect on endurance limit. The influence of surface finish on the S–N curve and endurance limit is presented in Fig. 17, which shows that surface roughness has full control on the fatigue life for machined aluminium alloy components. The samples with lower surface roughness give higher fatigue strength at low as well as high cycle strengths. The endurance limit also reduces with the increase of surface roughness. The influence of residual stress is insignificant due to the removal of top surface of sample through polishing processes. The influence of the surface roughness hybrid parameters D_q (root mean square slope) and λ_q (spacing between local peaks and valleys) on fatigue endurance limit is less than that of the arithmetic mean surface finish R_a . The shape of grooves as well as maximum height (R_t) of the surface profile are critical as the both factors inspire stress concentrations [70] and initiate crack under fatigue conditions [7]. Surface residual stress is often a better display of fatigue behaviour than surface features when the surface roughness R_a is in range of 2.5–5 μm . This influence decreases with the increase of temperature because of the easing of residual stress with thermal exposure [71]. These are not due to the change of surface finish, but because of modifications of the integrity on the machined surfaces owing to the machining operation [19].

Non-traditional machining methods influence workpiece surface integrity in different ways, and hence the fatigue

Table 2 Effect of machining on fatigue strength of stainless steel

Reference and test type	Machining process	Conclusion
Ref. [5] Rotating bending fatigue tests at 3 800 r/min	Turning was performed in wet condition using inserts with 0.2 mm, 0.4 mm, 0.8 mm in nose radius where feeds were 0.05 mm/r, 0.1 mm/r, 0.2 mm/r, 0.3 mm/r, 0.4 mm/r, the depth of cut was 0.5 mm and the speed was 80 m/min	The residual stress becomes more compressive as the feed rate increases. An increase of the nose radius of the insert reduces the compressive residual stresses. An increase of compressive residual stress increases the fatigue life of turned specimens
Ref. [39] Axial fatigue test on a 100 kN amslervibrofore at stress ratio 0.1	Dry turning was performed at the speed of 200 m/min, feed rate of 0.06 mm/r and depth of cut of 0.5 mm Cylindrical grinding was performed at wheel speed of 23 m/s, work speed of 8 m/min, infeed of 0.25 mm/pass and transverse of 0.13 mm/r using a consort alumina wheel and water soluble oil coolant	Superior fatigue strength was obtained with the turned specimens, particularly with PCBN cutting tools which produced the finest surface finish
Ref. [43] Rotating bending fatigue test	Turning at feed rates of 0.05 mm/r, 0.1 mm/r, 0.2 mm/r and 0.4 mm/r, corner radius of 0.2 mm and 0.8 mm, tool edge chamfer and sharp, depth of cut of 0.2 mm, cutting speed of 100 m/min	Higher fatigue life to the machined components can be achieved than that of virgin materials if compressive residual stresses and high hardness within surface layers can be induced by the cutting process. This can be obtained at a low feed rate, a small corner radius and a chamfered cutting edge tool
Ref. [50] A four-point rotary bending fatigue test	The effects of cutting speed, radial feed, tool wear, and two different cutting methods on the fatigue strength of threaded specimens were investigated for thread precision and tool life. The “compound straight” and “compound swivelled” thread cutting methods were used	Large variations of endurance limits of threaded specimens depend on machining conditions. The most significant factor is tool wear and the second strongest factor is cutting speed while the radial feed and thread cutting method were less influential. Thus, it is necessary to consider machining conditions for the fatigue design of precision threaded parts
Ref. [53] Tension-tension axial fatigue tests with load ratio of 0.1 at 300 MPa single maximum stress with 8 Hz frequency.	Fatigue test specimens were (i) hard turned surfaces with continuous white layers, (ii) hard turned surfaces with no white layers, (iii) ground surfaces (G), (iv) hard turned surfaces (i.e., continuous white layers) with super-finish, and (v) ground surfaces with super-finish. The cutting speed of 122 m/min, feed rate of 0.127 mm/r, depth of cut of 51 μ m and 255 μ m, cutting edge radill of 25 μ m Hone and 70 μ m Hone	Hard turned specimens exhibited at least as high a fatigue life as the baseline ground specimens. The white layers present on the surfaces of the hard turned specimens had no conclusive impact on the axial fatigue performance. The super finishing improved the performance of the hard turned specimens by an order of magnitude while producing only marginal improvements in the ground specimens. The fatigue life was directly proportional to both the surface compressive residual stress and the maximum compressive residual stress in the specimen
Ref. [54] Two fatigue tests were conducted using small taper roller bearing assemblies of a 120 mm outside diameter for the first test and large taper roller bearings of a 450 mm outside diameter for the second test	Hard turning was done using a high precision CNC lathe to create a bearing race profile. A CBN cutting tool with a 10° and 0.2 mm chamfer was used. No tool edge honing was applied The other group of bearings was ground. All the race surfaces were super-finished	Hard turned and super-finished bearings had at least as long fatigue life as ground and super-finished bearings. In one test, it was better than ground and super-finished bearings. The depth of compressive residual stresses is the major difference between hard turned and ground surfaces. Depth of cut does not produce a significant effect on residual stresses for precision hard turning. The primary deformation zone has a secondary effect on residual stresses. Feed rate only changes residual stress near the surface, but not in a deep layer. Tool edge geometry is the dominant factor for determining the residual stress profile

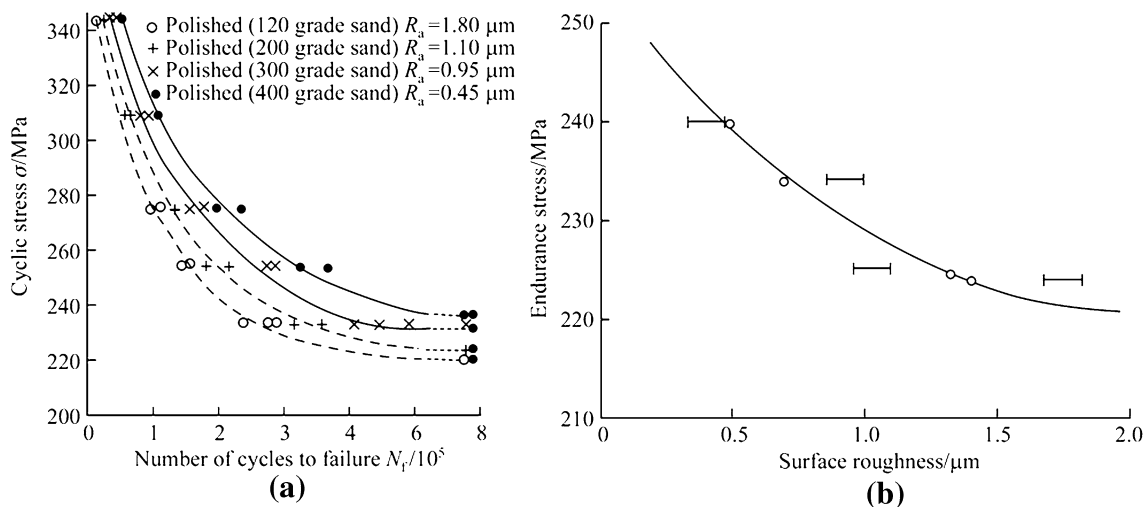


Fig. 17 Influence of surface roughness on a S–N curves and b endurance limit for aluminium alloys [69]

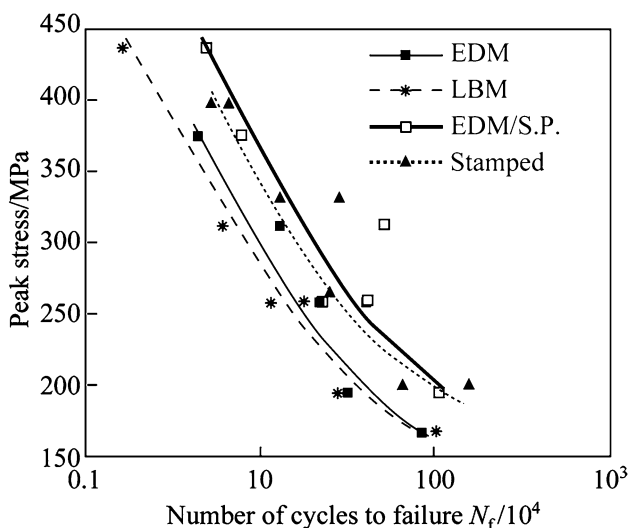


Fig. 18 S–N curves for Inconel 718 membranes: stamped, LBM, EDM and EDM-SP [65]

behaviour, subjected to the mechanism material removal. Figure 18 presents the influence of different non-conventional machining on S–N curves for Inconel 718 [65]. In the EDM process, the machined surface is often described by a heat affected zone with an upper hard, brittle and recast layers containing cracks and micro-cracks located normal to the machined surface. The machined surfaces also contain tensile residual stresses due to the thermal shrink age on the subsurfaces. Worse fatigue behaviour is achieved from the combination of these facts [18, 65, 72]. An identical circumstance is frequently noted from LBM, where thermal shrinkage of machined subsurfaces owing to the rapid solidification also incorporates unwanted tensile residual stresses [7].

AWJM mainly depends on the non-thermal mechanism of material removal, which occurs through the impacts of discrete grits suspended inside the fluid. Hence the method usually introduces compressive residual stresses on the machined surfaces, which contributes to better fatigue behaviour. Unfortunately, the machined surfaces frequently contain embedded grits [65, 73], usually with the diameter of 10–50 μm , which, if combined with a lower surface finish, may lead to stress concentration and considerably worsen fatigue performance [65].

5 Conclusions

The research on the influence of machining on fatigue behaviour is still at early stage. The fatigue strength of the machined components depends on the workpiece material, machining type and conditions. So far, the information in this research area is available only for very few alloys, such as titanium, steel, aluminium and nickel alloys. Based on our holistic review, the following key points can be summarised from the above investigations:

- (i) There is no clear trend on the effects of feed rate and speed on the fatigue strength of turned titanium alloys. The polishing process improves the surface roughness, but removes the surface layers with compressive residual stresses. This decreases the fatigue strength of polished specimens accordingly.
- (ii) The effects of residual stresses on the machined surfaces is more pronounced than that of surface roughness. The compressive residual stresses improve the fatigue strength

- and tensile stress reduces the fatigue strength by facilitating the crack growth.
- (iii) Grinding process induces tensile residual stresses on the machined surfaces due to the generation of high temperature. However milling process yields compressive residual stresses on the machined surfaces though surface roughness is worse in this case. Thus, a higher fatigue strength is achieved on the workpieces produced by the milling process.
 - (iv) Fatigue failure of titanium alloys is primarily due to the brittle fracture, in which the fracture surfaces show inter-lamellar, intra-lamellar and trans-lamellar fracture formations.
 - (v) EDM reduces the fatigue strength of titanium alloys due to the high population of micro-cracks and the presence of tensile residual stresses in recast layers. However, the electro-polishing improves the fatigue life by removing the recast layers.
 - (vi) Phase change is very common during the machining of steel, which contributes to the formation of residual stresses on the machined surfaces. Due to the turning process, compressive residual stresses in the axial and hoop directions are noted when there are continuous white layers, which contribute to volume expansion due to the phase transformation on the surfaces of the workpieces. Surface layers consisting of intermittent white layers may undergo tensile or compressive stresses depending on the amounts of present white layers.
 - (vii) The decrease in the feed allows the surface residual stress to shift towards compression residual stresses in both longitudinal and axial directions for steel. Higher compressive residual stresses cause higher fatigue life and the effect of residual stresses on fatigue life outperforms that of surface roughness. An increase in the nose radius of the insert causes a decrease in compressive residual stress. An increase in cutting speed increases the local temperature near the cutting tip, thus resulting in surface tensile stresses. If this temperature is high enough, the martensite transformation may occur in quenching by generating compressive residual stresses. High compressive residual stresses and high surface hardness are necessary to benefit a longer fatigue life. Smaller corner radius tool with chamfer increases surface hardness, which means the plastic deformation within the machined surface layer becomes more pronounced.
 - (viii) Steel surfaces generated from grinding have weaker fatigue performance when compared to that of turning and milling for the similar reasons as noted for titanium alloys.
 - (ix) Non-conventional machining such as EDM and laser machining generates a network of micro-cracks in addition to tensile residual stresses on the surfaces of all the materials. This network of cracks changes substantially whatever the level of applied stresses. The cracks initiate and propagate, and form a continuous network, leading to the premature failure of the specimens prepared by the EDM, as opposed to those prepared by traditional machining processes with better surface integrity and lower roughness.
 - (x) AWJM produces compressive residual stresses on the Inconel 718 machined surfaces. However, the machined surfaces often contain embedded grits that can act as stress concentration sites to significantly degrade fatigue performance if combined with a high work-piece surface roughness.

References

1. Bentley S, Mantle A, Aspinwall D (1999) The effect of machining on the fatigue strength of a gamma titanium aluminide intermetallic alloy. *Intermetallics* 7(8):967–969
2. Zhang LC, Kiat E, Pramanik A (2009) A briefing on the manufacture of hip joint prostheses. *Adv Mater Res* 76–78:212–216
3. Pramanik A, Zhang LC, Chen YQ (2010) Efficient machining of artificial hip joint components. *Adv Mater Res* 97–101:2269–2272
4. Zahavi E, Torbilo V, Press S (1996) *Fatigue design: life expectancy of machine parts*. CRC Press, Boca Raton
5. Javidi A, Rieger U, Eichseder W (2008) The effect of machining on the surface integrity and fatigue life. *Int J Fatigue* 30(10): 2050–2055
6. Zlatin N, Field M (1973) Procedures and precautions in machining titanium alloys. In: *titanium science and technology*. Springer, New York, pp 489–504
7. Novovic D, Dewes R, Aspinwall D et al (2004) The effect of machined topography and integrity on fatigue life. *Int J Mach Tools Manuf* 44(2):125–134
8. Dieter GE (2015) *Mechanical metallurgy*. McGraw-Hill, New York
9. Koster W, Field M (2001) Effects of machining variables on the surface and structural metals. In: *proceedings of the North American manufacturing research conference, SME*
10. Mantle A, Aspinwall D (1997) Surface integrity and fatigue life of turned gamma titanium aluminide. *J Mater Process Technol* 72(3):413–420
11. Taylor D, Clancy O (1991) The fatigue performance of machined surfaces. *Fatigue Fract Eng Mater Struct* 14(2–3):329–336

12. Pramanik A, Littlefair G (2014) Developments in machining of stacked materials made of CFRP and titanium/aluminum alloys. *Mach Sci Technol* 18(4):485–508
13. Pramanik A, Basak A, Islam MN (2015) Effect of reinforced particle size on wire EDM of MMCs. *Int J Mach Mach Mater* 17(2):139–149
14. Jha SK, Szczepanski CJ, Golden PJ et al (2012) Characterization of fatigue crack-initiation facets in relation to lifetime variability in Ti-6Al-4V. *Int J Fatigue* 42:248–257
15. Zhang H (1995) Investigation of machinability of titanium aluminides. Dissertation. University of Birmingham, Birmingham
16. Xie Q, Bayoumi AE, Kendall LA et al (1989) A study on residual stresses and tool wear induced by machining processes. In: Proceedings of North American manufacturing research conference XVII
17. Field M, Kahles JF, Cammett J (1972) Review of measuring methods for surface integrity. *CIRP* 21(2):219–238
18. Trail S, Bowen P (1995) Effects of stress concentrations on the fatigue life of a gamma-based titanium aluminide. *Mater Sci Eng A* 192:427–434
19. Koster W, Field M (1973) Effect of machining variables on the surface and structural integrity of Ti. In: proceedings of the North American metal working research conference
20. Klocke F, Welling D, Dieckmann J (2011) Comparison of grinding and wire EDM concerning fatigue strength and surface integrity of machined Ti6Al4V components. *Procedia Eng* 19:184–189
21. Janeček M, Nový F, Stráský J et al (2011) Fatigue endurance of Ti-6Al-4V alloy with electro-eroded surface for improved bone in-growth. *J Mech Behav Biomed Mater* 4(3):417–422
22. Mower TM (2014) Degradation of titanium 6Al-4V fatigue strength due to electrical discharge machining. *Int J Fatigue* 64:84–96
23. Stráský J, Janeček M, Hrcuba P et al (2011) The effect of microstructure on fatigue performance of Ti-6Al-4V alloy after EDM surface treatment for application in orthopaedics. *J Mech Behav Biomed Mater* 4(8):1955–1962
24. Mueller J, Rack H, Wagner L (2007) Effects of supra- and subtrans us heat treatments on fatigue performance of Ti-6Al-4V. In: *Ti-2007 Sci Technol* 383–386
25. Leinenbach C, Eifler D (2006) Fatigue and cyclic deformation behaviour of surface-modified titanium alloys in simulated physiological media. *Biomaterials* 27(8):1200–1208
26. Sharman A, Aspinwall D, Dewes R et al (2001) The effects of machined workpiece surface integrity on the fatigue life of γ -titanium aluminide. *Int J Mach Tools Manuf* 41(11):1681–1685
27. Campbell J, Rao KV, Ritchie R (1997) On the role of microstructure in fatigue-crack growth of γ -based titanium aluminides. *Mater Sci Eng A* 239:722–728
28. Murali MS, Yeo SH (2005) Process simulation and residual stress estimation of micro-electrodischarge machining using finite element method. *Jpn J Appl Phys* 44(7R):5254
29. Stefanescu D, Truman C, Smith D et al (2006) Improvements in residual stress measurement by the incremental centre hole drilling technique. *Exp Mech* 46(4):417–427
30. Haşçalık A, Çaydaş U (2007) Electrical discharge machining of titanium alloy (Ti-6Al-4V). *Appl Surf Sci* 253(22):9007–9016
31. Yu JW, Xiao P, Liao YS et al (2009) Surface integrity in electrical discharge machining of Ti-6Al-4V. *Adv Mater Res* 76–78:613–617
32. Aspinwall D, Soo S, Berrisford A et al (2008) Workpiece surface roughness and integrity after WEDM of Ti-6Al-4V and Inconel 718 using minimum damage generator technology. *CIRP Ann-Manuf Technol* 57(1):187–190
33. Newman JC Jr, Phillips EP, Swain MH et al (1992) Fatigue mechanics: an assessment of a unified approach to life prediction. *Int J Fatigue* 15(1):68
34. Pramanik A, Basak A, Islam MN et al (2015) Electrical discharge machining of 6061 aluminium alloy. *Trans Nonferrous Met Soc China* 25(9):2866–2874
35. Golden PJ, John R, Porter Iii WJ (2010) Investigation of variability in fatigue crack nucleation and propagation in alpha + beta Ti-6Al-4V. *Procedia Eng* 2(1):1839–1847
36. Kahles J, Field M (1967) Paper 4: surface integrity—a new requirement for surfaces generated by material-removal methods. doi:10.1243/PIME_CONF_1967_182_301_02
37. Griffiths B (1987) Mechanisms of white layer generation with reference to machining and deformation processes. *J Tribol* 109(3):525–530
38. Thiele JD, Melkote SN, Peascoe RA et al (1999) Effect of cutting-edge geometry and workpiece hardness on surface residual stresses in finish hard turning of AISI 52100 steel. *J Manuf Sci Eng* 122(4):642–649
39. Abrão AM, Aspinwall DK (1996) The surface integrity of turned and ground hardened bearing steel. *Wear* 196(1):279–284
40. Sasahara H, Obikawa T, Shirakashi T (2004) Prediction model of surface residual stress within a machined surface by combining two orthogonal plane models. *Int J Mach Tools Manuf* 44(7–8):815–822
41. Outeiro JC, Dias AM, Lebrun JL (2004) Experimental assessment of temperature distribution in three-dimensional cutting process. *Mach Sci Technol* 8(3):357–376
42. Schwach DW, Guo YB (2006) A fundamental study on the impact of surface integrity by hard turning on rolling contact fatigue. *Int J Fatigue* 28(12):1838–1844
43. Sasahara H (2005) The effect on fatigue life of residual stress and surface hardness resulting from different cutting conditions of 0.45% C steel. *Int J Mach Tools Manuf* 45(2):131–136
44. Abhang LB, Hameedullah M (2010) Chip-tool interface temperature prediction model for turning process. *Int J Eng Sci Technol* 2(4):382–393
45. García NV, Gonzalo O, Bengoetxea I (2012) Effect of cutting parameters in the surface residual stresses generated by turning in AISI 4340 steel. *Int J Mach Tools Manuf* 61:48–57
46. Rech J, Moisan A (2003) Surface integrity in finish hard turning of case-hardened steels. *Int J Mach Tools Manuf* 43(5):543–550
47. M'Saoubi R, Outeiro JC, Changeux B et al (1999) Residual stress analysis in orthogonal machining of standard and resulfurized AISI 316L steels. *J Mater Process Technol* 96(1–3):225–233
48. Fetullazade E, Akyildiz HK, Saritas S (2010) Effects of the machining conditions on the strain hardening and the residual stresses at the roots of screw threads. *Mater Des* 31(4):2025–2031
49. Field M (1971) Review of surface integrity of machined components. *Ann CIRP* 20(2):153–163
50. Akyildiz HK, Livatyali H (2010) Effects of machining parameters on fatigue behavior of machined threaded test specimens. *Mater Des* 31(2):1015–1022
51. Arola D, Williams CL (2002) Estimating the fatigue stress concentration factor of machined surfaces. *Int J Fatigue* 24(9):923–930
52. Dahlman P, Gunnberg F, Jacobson M (2004) The influence of rake angle, cutting feed and cutting depth on residual stresses in hard turning. *J Mater Process Technol* 147(2):181–184
53. Smith S, Melkote SN, Lara-Curzio E et al (2007) Effect of surface integrity of hard turned AISI 52100 steel on fatigue performance. *Mater Sci Eng A* 459(1):337–346
54. Matsumoto Y, Hashimoto F, Lahoti G (1999) Surface Integrity generated by precision hard turning. *CIRP Ann Manuf Technol* 48(1):59–62

55. Hashimoto F, Guo YB, Warren AW (2006) Surface Integrity difference between hard turned and ground surfaces and its impact on fatigue life. *CIRP Ann Manuf Technol* 55(1):81–84
56. Guo YB, Yen DW (2004) Hard turning versus grinding—the effect of process—induced residual stress on rolling contact. *Wear* 256(3–4):393–399
57. Matsumoto Y, Magda D, Hoepfner DW et al (1991) Effect of machining processes on the fatigue strength of hardened AISI 4340 steel. *J Manuf Sci Eng* 113(2):154–159
58. Matsumoto Y, Barash MM, Liu CR (1986) Effect of hardness on the surface integrity of AISI 4340 steel. *J Manuf Sci Eng* 108(3):169–175
59. Pramanik A (2016) Electrical discharge machining of MMCs reinforced with very small particles. *Mater Manuf Process* 31(4):397–404
60. Ghanem F, Sidhom H, Braham C et al (2002) Effect of near-surface residual stress and microstructure modification from machining on the fatigue endurance of a tool steel. *J Mater Eng Perform* 11(6):631–639
61. Pramanik A, Littlefair G (2015) Machining of titanium alloy (Ti-6Al-4V)—theory to application. *Mach Sci Technol* 19(1):1–49
62. Ghanem F, Braham C, Sidhom H (2003) Influence of steel type on electrical discharge machined surface integrity. *J Mater Process Technol* 142(1):163–173
63. Mamalis AG, Vosniakos GC, Vaxevanidis NM (1987) On the surface integrity of mechanically and thermally worked metal plates. *Adv Technol Plast* 1:407–414
64. Bouzid Saï W, Ben SN, Lebrun JL (2001) Influence of machining by finishing milling on surface characteristics. *Int J Mach Tools Manuf* 41(3):443–450
65. Fordham J, Pilkington R, Tang C (1997) The effect of different profiling techniques on the fatigue performance of metallic membranes of AISI 301 and Inconel 718. *Int J Fatigue* 19(6):487–502
66. Suhr R (1988) High cycle fatigue(in high temperature materials). *Inst Met Mech Test* 226–287
67. Suresh S (1998) *Fatigue of materials*. Dissertation. Cambridge University Press, Cambridge
68. Siebel E (1957) Influence of surface roughness on the fatigue strength of steels and non-ferrous alloys. *Eng Dig* 18:109–112
69. Bayoumi MR, Abdellatif A (1995) Effect of surface finish on fatigue strength. *Eng Fract Mech* 51(5):861–870
70. Leverant G, Langer B, Yuen A et al (1979) Surface residual stresses, surface topography and the fatigue behavior of Ti-6Al-4V. *Metall Trans A* 10(2):251–257
71. Koster, W (1991) Effect of residual stress on fatigue of structural alloys. Practical applications of residual stress technology, conference proceedings, Indianapolis, Indiana
72. Griffiths B (2001) *Manufacturing surface technology: surface integrity and functional performance*. Elsevier, Amsterdam
73. Hirano K, Enomoto K, Hayashi E et al (1997) Effects of water jet peening on corrosion resistance and fatigue strength of type 304 stainless steel. *J Soc Mater Sci Jpn* 45(7):740–745