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Contribution of machining to the fatigue behaviour of metal matrix composites (MMCs) of varying reinforcement size

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Abstract

The high cycle constant stress amplitude fatigue performance of metal matrix composite (MMC) components machined by a milling process was investigated in this study as a function of machining speed, feed rate and reinforcement particle size. The presence of reinforcement and particle size were found to be the most influential factors that affected the fatigue life. In contrast to this, the effect of feed and speed on tool-particle interaction, strain hardening and heat generation during milling of MMCs were balanced in such a way that the contributions of feed and speed on fatigue life were negligible. The interactions of different parameters contributed significantly to the fatigue life which indicated that the modelling of fatigue life based on these three parameters was relatively complex. The fatigue life of the machined MMC samples increased with decreasing particle size and increasing feed. However, the fatigue life was not influenced by speed variation. The presence of smaller or no particles induced a complete separation of failed samples, in contrast to that of specimens containing larger reinforcing particles where crack growth was arrested or deflected by the reinforcing particles.

Keywords: Metal matrix composites (MMCs), fatigue life, feed, speed.

1. Introduction

Mechanical parts under a fluctuating stress fail at a much lower stress than those under static fracture stress due to the presence of fatigue mechanisms. This type of loading condition is very common and fatigue behaviour is therefore an important contributing factor in the service life of mechanical components. Factors that significantly influence the fatigue behaviour of components include material type and surface integrity [1]. The fatigue behaviour of composite materials such as metal matrix composites (MMCs) are more complex due to the presence of residual stresses and defects introduced during the primary manufacturing process, *e.g.*, casting, as a result of the coexistence of two phases with distinct mechanical and thermal properties. However, various properties of MMCs such as their strength-to-weight ratio, thermal stability, wear and corrosion resistance are superior to those of their constituent phases [2, 3] which has resulted in the widespread use of MMCs in numerous engineering applications including nuclear power stations, aerospace, aviation and defence where high strength-to-weight ratio is key to improving efficiency [4]. The surface integrity of machined MMC components depends on machining conditions in addition to the size and content of the reinforcing particles [1, 3, 5, 6]. Newly generated surfaces are typically under compressive residual stress with these surfaces often being damaged due to the presence of cavities left by the pull-out of particles. Such cavities are formed when particles located at the lower part of the cutting edge interact with the cutting tool [7]. The effect of speed and feed on residual stress for the machined non-reinforced alloy surface is different from that of MMCs during turning. Both longitudinal and transverse residual stresses on the matrix surface are tensile stresses that increase with an increase in speed and feed. On the other hand, reinforcing particles induce compressive residual stresses at the machined MMC surface through an indentation effect due to interactions with the cutting tool [1]. An increase in feed reduces the longitudinal compressive residual stress but has negligible influence on the transverse stress. The influence of speed on the residual stress of MMCs was also not significant [8]. At low feeds, the surface roughness of MMCs is controlled by particle fracture or pull-out; whereas at higher feeds, it was controlled by the feed [8, 9]. An increase in the reinforcement content increases the tensile strength and hardness of MMCs whilst simultaneously increasing wear of the cutting tool. The increase in particle volume fraction also has a negative effect on roughness. It appears that tool hardness influences the surface roughness and harder carbide tools produce a better surface finish compared to that of high speed steel (HSS) and titanium nitride coated HSS drills [1]. Therefore, machining speed, feed and reinforcing particles have a significant impact on the surface roughness and residual stress of MMCs. Previous literature reviews have shown that the residual stress and surface roughness significantly influences the service performance of machined components. Thus, a considerable amount of research has been performed to investigate processing parameters that significantly affect the residual stress [10]. For example, Brinksmeier [11] reported that the higher the depth of cut, the larger compressive residual stresses on the surface, whereas a higher feed rate increases the depth of stressed regions, which is in good accordance with König *et al*. [12]. In addition to this, Revel *et al*. [13] noted that higher cutting speeds induce higher compressive residual stresses in both the circumferential and tangential directions in a monolithic material. However, a higher depth of cut increases compressive residual stresses only at the machined surface, but not in depth. Dahlman *et al*. [14] reported that the rake angle and feed strongly influence residual stresses despite an insignificant effect of cutting depth on residual stresses. Results obtained by Abrão and Aspinwall [15] showed that hard turning induces higher compressive residual stresses when compared to grinding. There thus exists an optimal combination of tool geometry, workpiece hardness and cutting conditions that can increase compressive residual stresses in both the axial and circumferential directions [16]. Mittal and Liu [17] developed a model to predict the residual stresses below hard turned surfaces with their model incorporating machining parameters such that an optimal residual stress distribution could be proposed to enhance the fatigue performance of hard machined surfaces. Finally, Liu and Guo [18] found that the state of residual stresses within hard machined surfaces could be improved by controlling a sequential second cut.

The effect of machining conditions on the fatigue behaviour of machined components has been investigated only for select number of materials including titanium alloys, stainless steel, aluminium and Inconel 718 after applying different machining processes such as turning, milling, grinding, electro discharge machining and laser beam machining [1]. The fatigue failure of titanium alloys is usually associated with brittle fracture where the fracture surface shows inter-lamellar, intra-lamellar and trans-lamellar fractures [19]. Electrical discharge machining reduces the fatigue strength of titanium alloys due to micro-cracks and tensile residual stresses in the recast layers [20]. However, electro-polishing improves the fatigue life by removing recast layers [21-23]. The polishing process improves the surface roughness but simultaneously removes the surface layers that contain the compressive residual stresses within titanium alloys. This decreases the fatigue strength of the resulting polished specimens [21, 24, 25]. The compressive residual stress improves the fatigue strength whereas the presence of tensile stresses reduces the fatigue strength by facilitating the cracks to grow on the machined surface of titanium alloys. A higher fatigue strength is achieved on the workpieces produced by milling of titanium alloys when compared to grinding processes [25, 26]. Turning of stainless steel induces compressive residual stresses in the axial and hoop directions when there are continuous white layers, contributing to a volume expansion on the surface of stainless steel [27, 28]. Surface layers consisting of intermittent white layers may be subjected to tensile or compressive stresses, depending on the amount of white layers [29, 30]. The decrease in the feed will allow the surface residual stress to shift towards a compression residual stress in the longitudinal and axial directions for steel in order to increase the fatigue life. An increase in tool nose radius and cutting speed increases the shift towards tensile stresses [31, 32]. Steel surfaces generated from grinding have weaker fatigue performance when compared with those of turning and milling for similar reasons as noted for titanium alloys [14, 25, 33, 34]. Water jet machining produces compressive residual stresses on Inconel 718 machined surfaces. However, the machined surface often contains embedded grit, which, if combined with high workpiece surface roughness, act as stress concentrations to significantly degrade fatigue performance [35].

The above discussion indicates that there is no study on the effect of traditional machining on the fatigue behaviour of MMCs even though machined MMC components are frequently used in practical applications. In addition, the size of reinforcing particles significantly affect tool-particle interactions that contribute to the integrity of the machined surface. Therefore, in order to address this issue, the objective of this study is to investigate the effect of speed, feed and reinforcement size on the fatigue performance of MMC components produced by milling processes so that MMC parts can be designed more efficiently.

2. Scope

Fatigue behaviour significantly affects the design and manufacturing of different parts. Fatigue analysis is one of the main processes carried out by designers during the design stage to predict the possibilities of fatigue. This helps to reduce time and other resources following manufacturing. Fatigue affects the product as a whole or induces defects in the components of the product, which significantly reduces the functionality and performance of the product. A clear understanding of fatigue and associated necessary remedies can increase product reliability. Every product has an expected life span, after which it will perish. Fatigue analysts have to check thoroughly whether the product is likely to complete the expected life to make sure that no damage will occur before that and, even if any damage should happen, it should be possible to repair the component. A tactful designer will avoid expensive techniques and examine the possibilities of errors using simple analysis methods (http://enventureonline.blogspot.com.au/2011/10/importance-of-fatigue-analysis.html-Put). The present study was performed to remedy the lack of measured fatigue strength data for the most ubiquitous MMCs with surface conditions produced by a milling process.

The fatigue life data were analysed by applying the Taguchi design of experiment (DoE) method with the optimization of the robustness of manufacturing process data. A detailed explanation of the Taguchi DoE method can be found elsewhere [36]. This research is limited to MMCs with three different reinforcement sizes—0 (*i.e.*, matrix only, without reinforcing particles), 0.7 and 13 µm, and three different speeds— 20, 60 and 100 m/min and feeds— 0.05 & 0.01, 0.15 & 0.02, 0.35 & 0.03 mm/rev during milling operations. The first and second data sets of feed are for milling and drilling, respectively, with details being given in the next section. In general, average response values are used in conventional analysis of variance (ANOVA), which is particularly suitable for monitoring trends or changes in terms of variables. However, it does not provide the complete representation because it normally does not include data on the response scattering.

2. Methods and materials

Milling and drilling were performed on a Leadwell V-30 CNC machine by K10 cemented carbide tools on 6061 aluminum alloy and MMCs made of 6061 aluminum alloy reinforced with 10% SiC particles at particle diameters of 0.7 and 13 µm. As-received specimens (10 for each material) were machined into a particular shape for fatigue tests. The final flat dog-bone specimens have a neck radius of 75 mm and an overall length and width of 145 and 40 mm, respectively, as shown in Figure 1. A sufficiently sized hole (8 mm diameter) was drilled through the specimen center so that the stress concentration can be controlled and fatigue failure can be forced to propagate around those areas [37]. The variations of machining parameters and materials are presented in Table 1 whilst all of the experiments are listed in Table 2.

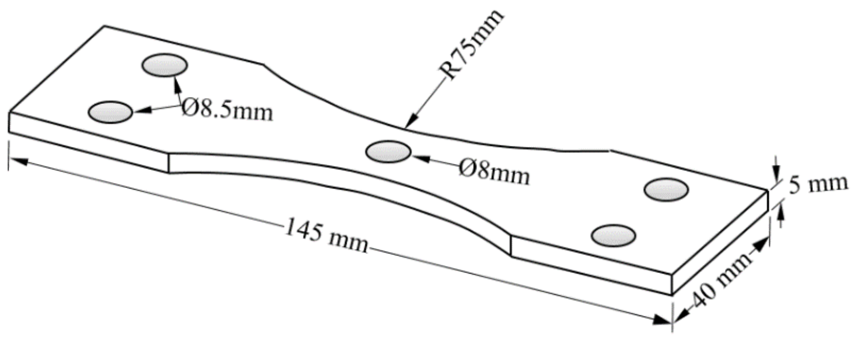


Figure 1: Schematic diagram of a flat dog-bone specimen

Table 1: Parameters and range

Parameters	Symbol	Values		
		Low (0)	Medium (1)	High (2)
SiC_p particle size (µm)	A	No Particles	0.7	13
Cutting Speed (m/min)	B	20	60	100
Feed Rate (mm/rev)	C	0.05 (milling) & 0.01 (drilling)	0.15 (milling) & 0.02 (drilling)	0.35 (milling) & 0.03 (drilling)

Table 2: Milling and drilling parameters

Experiments	SiC_p particle size (µm)	Cutting speed (m/min)	Milling feed rate (mm/rev)
1	Only matrix material	20	0.05
2		20	0.15
3		20	0.35
4		60	0.05
5		60	0.15
6		60	0.35
7		100	0.05
8		100	0.15
9		100	0.35
10	0.7	20	0.05
11		20	0.15
12		20	0.35
13		60	0.05
14		60	0.15

15		60	0.35
16		100	0.05
17		100	0.15
18		100	0.35
19	13	20	0.05
20		20	0.15
21		20	0.35
22		60	0.05
23		60	0.15
24		60	0.35
25		100	0.05
26		100	0.15
27		100	0.35

The tool paths along the specimens are outlined in Figure 2. The milling tool to perform peripheral and axial milling operations are both utilized on the specimens to remove excessive material. Drilling was conducted using the same milling tool to make the 8 mm hole in the center of the neck area of the specimens.

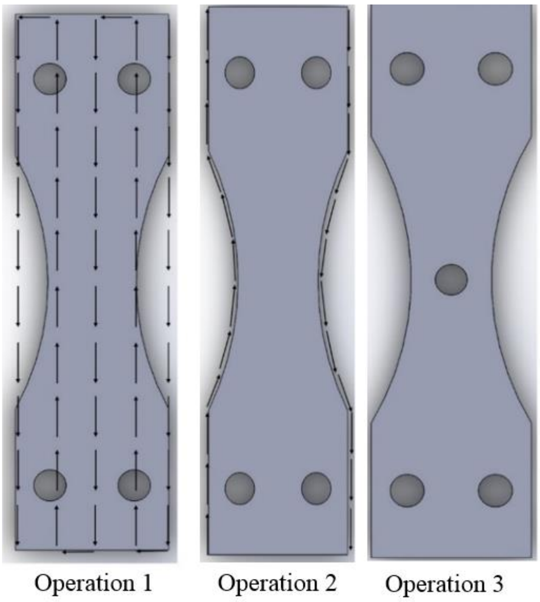


Figure 2 Tool path operations in machining

Reverse cycle fatigue tests were performed on a Schenck flexural fatigue machine. Each specimen was tested at 69.82 MPa (equivalent to a displacement amplitude of 0.58 mm) with a constant rotational speed of 1500 rpm. In the case where the specimens did not fail, the machine was stopped at 1×10^6 cycles.

3. Results

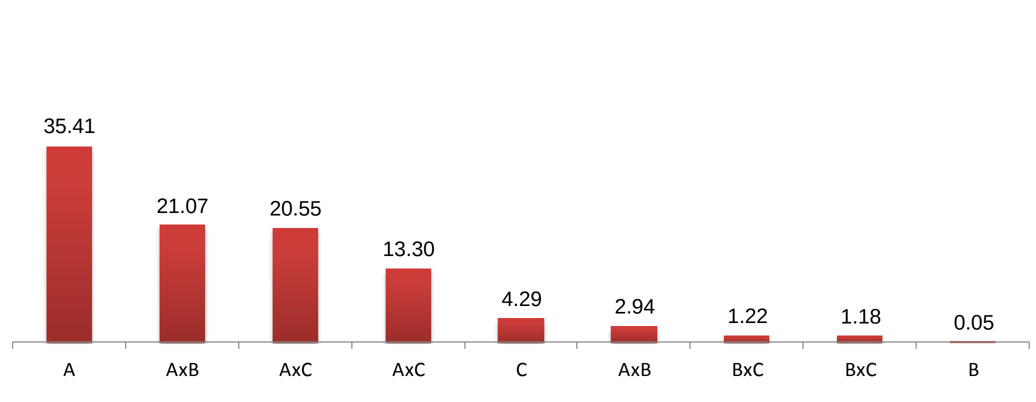
3.1 Fatigue life

Owing to the substantial amount of coordinate data and space constraints, only a sample of the coordinate data has been presented in this study though, for the analysis of the workpieces all the data were considered. The multi-variability of data obtained allowed the workpiece data to be present in numerous ways, with a Pareto ANOVA analysis being conducted on the quality test parameters.

The Pareto ANOVA analysis for diameter error given in Table 3 reveals that the size of the reinforcing particles (A) has the most significant effect on the fatigue life with a influence ratio (P ≅ 35.41%), followed by the interaction between particle size and milling speed (A×B) (P ≅ 21.07%). The third contributing factor is the interaction between particle size and milling feed (A×C) (P ≅ 20.55 %). The fourth and fifth contributing factors are second interactions between particle size and milling feed (A×C) (P ≅ 13.30 %), and, milling feed (C) (P ≅ 4.29 %), respectively. The individual contributions of speed (B) and feed (C) are 0.05 and 4.29%, respectively, and considered to be non-significant factors. Therefore, it is clear that the summation of contributions of interactions among parameters (P ≅ 60.26 %) is much higher than that of individual parameters (P ≅ 40.74 %), which indicates that the modelling of fatigue life of machined MMC components is relatively difficult.

Table 3 Pareto ANOVA analysis for fatigue life

Sum at factor level	Factor and interaction								
	A	B	AxB	AxB	C	AxC	AxC	BxC	BxC
0	2677.70	2463.50	2400.30	2447.20	2406.50	2367.40	2459.70	2478.00	2443.30
1	2529.80	2478.00	2338.50	2551.20	2448.40	2414.00	2300.10	2427.50	2454.30
2	2213.20	2479.20	2681.90	2422.30	2565.80	2639.30	2660.90	2515.20	2523.10
Sum of squares of difference (S)	337870.22	458.18	201041.36	28051.22	40914.86	126861.26	196130.24	11625.38	11222.48
Contribution ratio (%)	35.41	0.05	21.07	2.94	4.29	13.30	20.55	1.22	1.18



Cumulative contribution	35.41	56.48	77.03	90.33	94.62	97.56	98.78	99.95	100.00
Check on significant interaction	AXB two-way table								
Optimum combination of significant factor level	A0B2C2								

Since the interaction of A×B is significant, the A×B two-way table has been applied to select the optimum levels of A and B. From the A×B two-way table in Table 4, the optimum combination of factors A and B in order to achieve the longest fatigue life was determined as A0B2 due to this combination giving the highest response. Figure 3 shows that C2 provides for the maximum fatigue life. Therefore the best combination of input variables for maximising fatigue life was determined as A0B2C2, *i.e.*, having matrix material, highest level of speed (100 m/min), and highest level of feed (0.35 and 0.03 mm/rev). The absence of reinforcing particles (A0) was the best material to achieve longer fatigue life as shown in Fig 3.

Table 4 A×B two-way table

	A0			Total	**A1**			Total	**- A2**			Total
B0	266.5	241.0	348.5	856.0	267.4	253.4	257.0	777.8	256.3	296.6	276.8	829.7
B1	279.0	260.2	335.7	874.9	309.4	320.6	275.4	905.4	216.4	240.6	240.7	697.7
B2	284.7	305.3	356.8	946.8	286.7	311.5	248.4	846.6	240.1	219.2	226.5	685.8

The variation in the fatigue for those three input parameters shown in Figure 3 was obtained from the traditional method. It is shown that the maximum fatigue life is achieved for matrix material only, at the speed of 100 m/min, and feeds of 0.35 (0.03 for drilling) mm/rev. All these show that the fatigue life of machined components increases with a decrease in particle size and increase in feed, but that any variation of speed does not have a noticeable effect on the fatigue life.

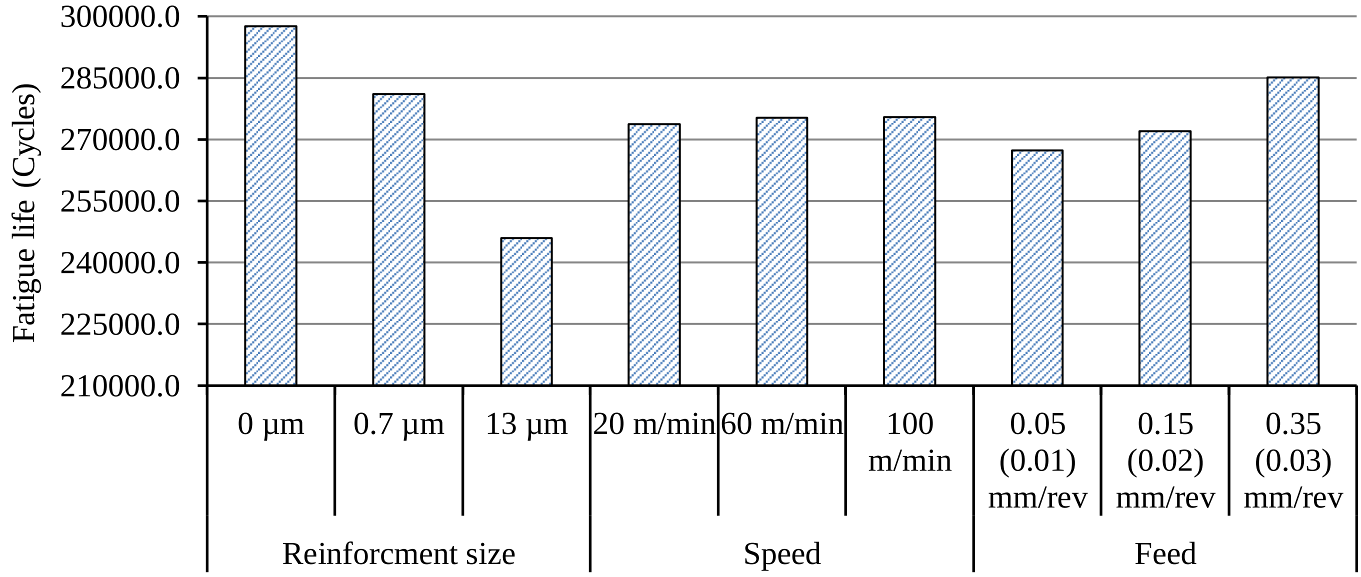


Figure 3 Average fatigue life for three processing parameters in this study

The fatigue life of the machined components are mainly controlled by the material properties and surface integrity induced by machining processes. It is well know that presence of crack and tensile residual reduces the fatigue life. In this case, the higher size of particles are more likely to fracture and the amount of cracks increase with the increase of particle size. Therefore, the fatigue life decreases with the increase of reinforcement size. The speed has minor influence on the residual stress and surface finish [8] which results in negligible influence of speed on fatigue life. Lower feed indices compressive residual stress, lower strain and higher particle fracture. On the other hand, the higher feed gives tensile residual stress, higher strain and less particle fracture. The compressive stress increases fatigue life and higher strain workharden materials which increases the fatigue life but the particle fracture reduces the fatigue life. Therefore, all these actions interact each other when the feed is varied. It seems that when the feed increases, higher work hardening and reduced particle fracture take over the tensile residual stress which lead to the increase of fatigue life.

3.2 Fatigue fracture

The failed workpiece specimens due to the propagation of fatigue cracks are presented in Figures 4 ‐ 6 with Figure 4 showing the effect of particle size on crack propagation at low and high values of fixed parameters. In this case, when the particle size varies, the feed and speed remain as fixed parameters. Only the high and low values of relevant fixed parameters have been considered in Figures 4 ‐ 6 to see the greatest effect on the results. Similarly, Figures 5 and 6 show the effect of feed and speed, respectively, on crack propagation at low and high values of fixed parameters. It is established from the previous section that the particle size has the most significant effect on the fatigue life as the properties of MMCs change due to the variation of particle size. Therefore, it is self-evident that the fracture due to fatigue cracks is not similar when particle size varies in MMCs. However, Figures 5 and 6 show that fatigue fractures due to the variations of feed and speed are also different even though the contributing effect of these parameters on the fatigue life is negligible, as depicted in Table 3.

Figures 4 ‐ 6 clearly show that complete fracture occurs for the specimens without reinforcements at all conditions (except the specimens machined at a higher speed of 100 m/min) and low feeds of 0.05 mm/rev in milling and 0.01 mm/rev in drilling. When the particle size is 0.7 µm, a complete separation of specimens takes place only when those were machined at a higher speed of 100 m/min and a higher feed of 0.35 mm/rev in milling and 0.03 mm/rev in drilling. In the case of MMCs reinforced with 13 µm particles, the complete separation of specimens occurs only when those were machined at a higher speed of 100 m/min and lower feeds of 0.05 mm/rev in milling and 0.01 mm/rev in drilling, as illustrated in Figure 5, and a lower speed of 20 m/min and higher feeds of 0.35 mm/rev in milling and 0.03 mm/rev in drilling as shown in Figure 6.

Figures 4 ‐ 6 also demonstrate that, regardless of materials and machining conditions, fatigue cracks start at the edge of the drilled hole on the flat surface in only one place. Therefore, the intention to generate the cracks in a specific position was successful. After the crack generation, it starts to propagate along the flat surface as well as along the depth of the drilled hole. The failure due to fatigue occurs along the transverse axis of the specimen. The propagation speed in the transverse direction is faster than that in the depth direction because in many cases the cracks crosses the longer longitudinal width before crossing the thickness of shorter depth. In most of the cases, the cracks crossed the drilled hole along its diameter (*i.e.*, through the hole centre). However, in one case, the crack obviously neither crossed the drilled hole along its diameter nor went through the hole centre when the material was reinforced with 13 µm particles and machined at the lower speed and feed, as shown in Figure 4.

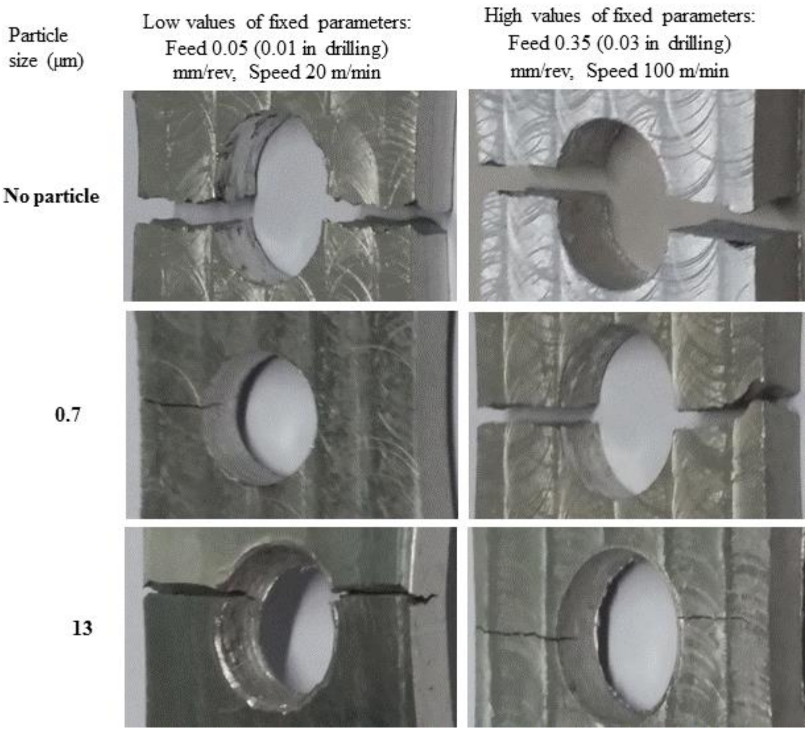


Figure 4 Effect of particle size on fatigue fracture at low (Feed 0.05 mm/rev, Speed 20 m/min and high (Feed 0.35 mm/rev, Speed 100 m/min) values of fixed parameters.

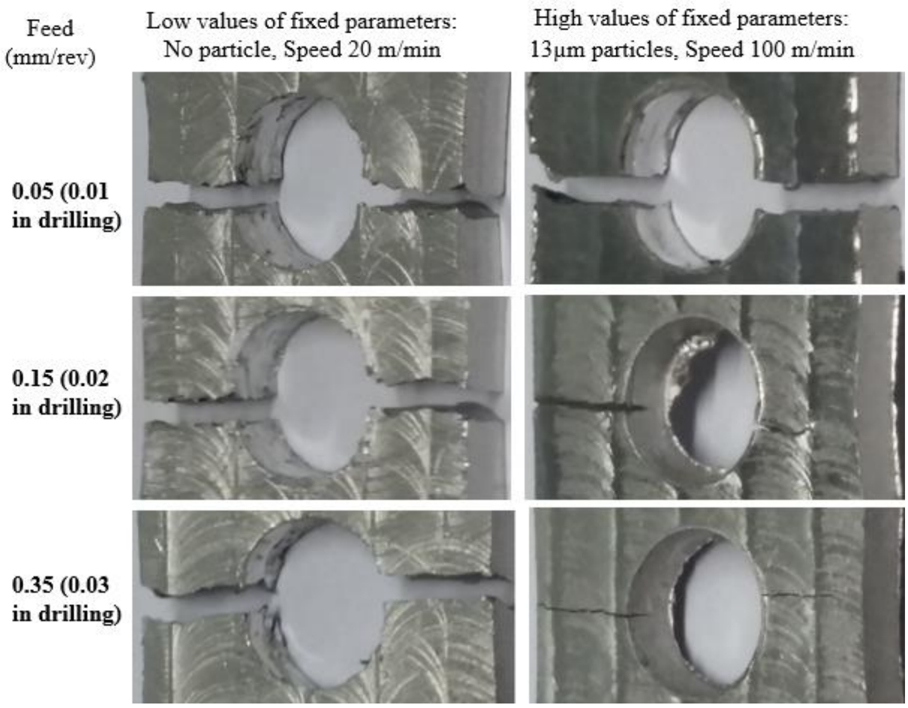


Figure 5 Effect of feed on fatigue fracture at low (no particle, speed 20 m/min) and high (13µm particles, speed 100 m/min) values of fixed parameters.

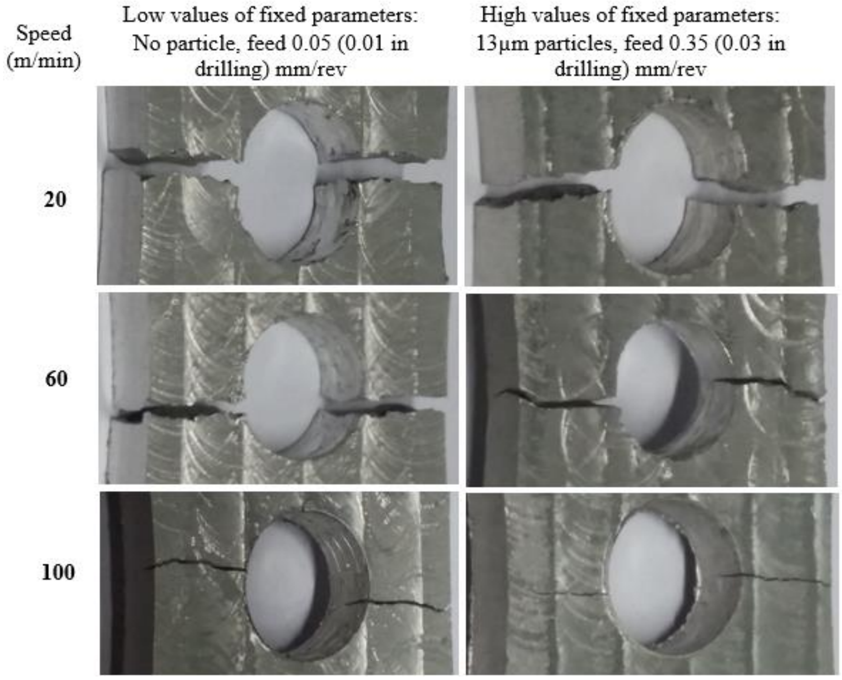


Figure 6 Effect of speed on fatigue fracture at low (no particle, feed 0.05) and high (13µm particles, feed 0.35 mm/rev) values of fixed parameters.

4. Discussion

The dispersion of ceramic particles in metallic alloys induces a number of microstructural changes in metallic matrices such as enhanced dislocation density, smaller grain size, weaker texture, *etc.*, which promotes homogeneous slip and inhibits the formation of slip bands. Thus, fatigue crack nucleation in MMCs reinforced with particles occurred at surface inclusions and clusters not at slip bands [38, 39]. However, it has been shown that the presence of reinforcement can increase the fatigue life, depending on the strength of the matrix and reinforcement/matrix interface [40], where surface defects have been carefully minimized [41]. In most cases, fatigue life has been reduced with the incorporation of reinforcements [42, 43]. The stresses transferred from the matrix to the particles increase during cyclic loading as a result of the cyclic hardening of the matrix. The stresses acting on the reinforcement and interface increase progressively during cyclic loading, thus increasing the number of damaged particles [44]. Work on commercial Al alloys reinforced with either Al_2O_3 or SiC particles [45, 46] or short Al_2O_3 fibres [47] has demonstrated that reinforcements are broken progressively during plastic deformation and that the probability of fracture increases with reinforcement size. As the average particle size increases, particulate fracture during deformation due to machining is expected to take place more rapidly and to be more extended with the negative effects of the reduction in the tensile strength of composites and precipitation of the final fracture [48]. During machining, regardless of machining conditions, severe plastic deformation occurs in the newly generated surfaces. Therefore, the fracture of reinforcing particles occurs due to the plastic deformation as well as interactions with the cutting tool. The fractured particles damage the machined surfaces and induce micro-cracks. This damage become severe and the number of micro-cracks rises with the increase of reinforcing particle size. Therefore, the presence and size of the reinforcement are the most influential factors on the fatigue life of machined MMCs, as shown in

Table 3. It is also evident that the presence of particles reduces the fatigue life that decreases with the increase in particle size (Figure 3).

Regardless of machining conditions during the milling process of MMCs, newly generated surfaces are embedded with cracks and cavities that are generated from fracture and pull out of reinforcing particles. Therefore, individual contributions of feed and speed on the fatigue life are negligible, as shown in Table 3. The machining of MMCs affects the machined surface in three ways, namely, work hardening, particle fracture and temperature generation. At low feed (cut-thickness), the area of cut is small and the entire cut area may have been work hardened by the successive tool pass. In this case, the generated temperature is low but cracks increase significantly due to the increase in tool-particle interactions. At the higher feed, indentation effects of particles as well as tool–particle interactions decrease for the same length of machined workpiece. Additionally, effects of temperature increase with the increase in feed. Thus, high compressive residual stress values at low feed and lower stress values at the higher feed can be expected. The effects of tool-particle interaction override the effect of work hardening, therefore, fatigue life is lower at the low feed. On the other hand, cracks and compressive stress and the temperature increases with the increase in feed. All these phenomena balance to result in lower defects on the machined MMC surface and longer fatigue life.

The influence of temperature is comparatively small at a low cutting speed but with the increase of speed its influence increases as well. The impact of mechanical factors also increases due to the increase in strain rate. With the speed variation, it appears that mechanical and thermal effects balance out, resulting in negligible compressive residual stresses on the machined MMC surfaces. It appears that the generation of cracks does not change with the speed variation due to the unchanged number of tool-particle interactions. Therefore, the fatigue life of machined MMC specimens does not vary noticeably when the speed varies.

Crack propagation follows the weakest path in the material as the crack circumvents the obstacles. Small fluctuations in the crack driving force when the crack interacts with microstructural features may induce large variations in the growth rate or even completely arrest crack growth. Grain boundaries are typical obstacles to crack propagation in metallic alloys [49], and the roughness of the crack surfaces was often dictated by the grain size as the crack changed the direction of crack propagation from grain to grain [50]. The stress field around the crack tip was not intense enough to fracture ceramic reinforcements [51-53]. The crack propagated mainly through the metallic matrix and very few broken reinforcements were observed either around the fatigue crack tip or along the crack path, as shown in Figure 7. On the contrary, the cracks growing towards reinforcements were deflected along or close to the reinforcement–matrix interface. As a result, the roughness of the crack profile was partially dictated by the grain boundaries (which also acted as obstacles to crack propagation) and partially by inter-particle distance and particle size. Changes in the average reinforcement size from 4.5 to 11.4 μm [54] or from 3 to 21 μm [55] enhanced the crack growth resistance, thus further promoting much higher closure levels in composites. Therefore, it was observed that the specimens without reinforcements often completely fracture. Nevertheless, MMC specimens with reinforcements in bigger sizes do not fracture completely despite having shorter fatigue life.

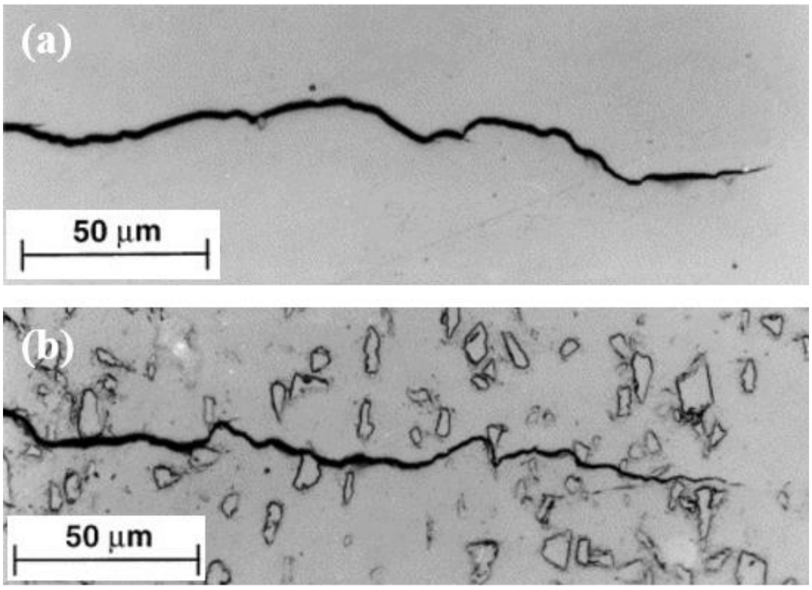


Fig. 7 The propagation of fatigue cracks in (a) monolithic metal alloy and (b) MMCs reinforced with particles [56]

5. Conclusions

Individual contributions of the machining parameters considered in this work on the fatigue life of machined specimens are negligible. However, the interactions of machining parameters with the size of the reinforcement significantly affect the fatigue life. The above investigation can be concluded as follows:

(a) Fracture and pull out of reinforcing particles in MMCs dominate machined surfaces by forming cracks and cavities due to plastic deformation and tool-particle interactions. Such a trend increases with the increase in reinforcing particle size. Therefore, the presence of reinforcement and the size of reinforcing particles are the most influential factors to the fatigue life of machined MMC specimens.

(b) The effect of feed and speed on tool-particle interactions, strain hardening and heat generation during the milling process of MMCs are balanced in a way that the contributions of feed and speed to the fatigue life of machined MMC specimens are negligible.

(c) The interactions of particle size–feed and particles size–speed contributes significantly to the fatigue life of machined MMC specimens. The summation of these contributions is much more than the contributions of individual parameters. Therefore, the modelling of fatigue life based on these three parameters becomes very complex.

(d) Bigger particles and lower feeds induce more defects on machined MMC surfaces whilst the speed does not have a noticeable effect on machined surfaces. Therefore, fatigue life increases with the decrease in particle size and increase in feed. However, the fatigue life does not change with the speed variation.

(e) The propagation of fatigue cracks is arrested or deflected by reinforcing particles. The bigger particles possess a higher capability to stop crack propagation. Therefore, machined MMC specimens reinforced with smaller or no particles often completely separate as opposed to the counterparts containing bigger reinforcing particles.

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