A REVIEW ON CONVENTIONAL AND LASER ASSISTED MACHINING OF ALUMINIUM BASED METAL MATRIX COMPOSITES

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Abstract:

Aluminum based Metal Matrix Composites (Al-MMC) have been found in different industrial applications due to their excellent properties compared to conventional materials. Machining of these composites is difficult due to their hard particle reinforcements. The wider usage of these composites is limited because of high machining cost and excessive tool wear caused by conventional machining. Because of increasing demands in industries, any improvement of conventional machining process or any other deployment of additional technique is directly related to higher productivity. Laser Assisted Machining has become an effective alternative to the conventional machining of these difficult- to-cut materials. This paper provides an overview of the conventional machining of MMCs and the potential of LAM. An attempt is made to give a better understanding of the operating conditions such as machining parameters and Laser parameters. Finally, the summary of the review is discussed and the scope for future research is presented.

1 Introduction

Nowadays, aluminum based Metal Matrix Composites (Al-MMCs) identified as low cost engineering materials, get wider applications including automotive, aerospace, medical, electronic and recreational industries because of their improved mechanical properties [1-3]. However, these composites are processed to near net shape, and subsequent machining is unavoidable for engineering products. Conventional machining of these ceramic particles, reinforced MMC are difficult to machine due to hard particle reinforcement, which results in increased tool wear, a poor machined surface, and high cutting force magnitudes. Also, while machining MMC, the particle reinforcement has a chance of pulling out fibres, damaging the sub-surface, and the formation of built-up edge [4-7]. In a recent research, Laser Assisted Machining is reported to be one of the suitable and hybrid machining methods for solving the above problems of machining MMCs. This paper presents a detailed literature review on the machinability of AL-MMCs by conventional and laser assisted machining. Also, this paper suggests a

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frame work for the selection of optimum parameters in LAM of Al-MMC for achieving higher productivity.

2 Conventional machining of Al -MMC

2.1 Introduction

Among various types of Al-MMCs, the particle reinforced composites have better mechanical and wear characteristics leading to wider usage in automotive and aerospace industries. The hardness of reinforced particles used in these MMCs is greater than in most of the cutting inserts, which results in high tool wear and subsequent subsurface damage, and consequently in shorter tool life, poor surface finish and higher cutting power [8] and [9]. Therefore, it is necessary to understand the mechanics during machining of MMCs. The following sections give a detailed review of the effect of the cutting force, surface integrity, tool wear, modeling and optimization of conventional machining of these MMCs.

2.2 Cutting force and power consumption

The cutting force acting on the cutting tool surface is highly dependent on the type of matrix, the reinforcement volume and the interface bond between matrix and reinforcement. In order to predict the generated cutting force during machining of these MMCs, the total specific cutting energy required for deformation has to be considered [10]. Kannan et al, have developed an analytical cutting force model based on energy consumption in the primary and secondary shear zone. This model has made an assumption that the energy in the primary deformation zone is three times stronger than the energy in the secondary deformation zone. However, the energy required for the ploughing force was not considered [11]. Pramanik et al, have developed an analytical model based on material removal mechanisms for predicting thrust forces and cutting forces. In this model, the predicted cutting force is the summation of the ploughing force, particle fracture force and chip formation force. The author has observed that the forces due to chip formation are much stronger than those due to ploughing and particle fracture. The author has however not considered the frictional force existing between the chip-tool interfaces [8]. Sikder and Dabade et al, have reported that the magnitude of the frictional force along the chip tool interface and the force due to particle debonding and ploughing forces must be considered and added to the total generated cutting forces [9] and [12].

Cutting parameters also play a significant role during machining of MMCs. It is observed that higher cutting speed (500 m/min and 700 m/min) and wear have increased the feed force and depth force [13]. On the other hand, an increase in feed resulted in an increased feed force and main cutting force [1], [14-16].

2.3 Surface quality and surface integrity

The surface quality is a characteristic of machined composites, which significantly influenced the product reliability and performance [17]. The better surface finish and surface integrity is observed to have been achieved with wiper cutting inserts than with fewer wiper cutting inserts, which perform a brushing operation on the machined surface of composites by the extended cutting edge [12]. Uday Dabade et al, have developed an ANN model to predict an optimal cutting condition for surface finish and to maximize material removal rate and results show that the surface finish is greatly affected by feed rate [18]. The cut depth has a negative effect on the surface finish and the sub-surface damage. A decrease in quality of surface finish is observed with an increase in cut depth and the sub-surface damage in machining of an Al/SiCp composite with uncoated tungsten carbide tools [19]. The surface roughness produced by the rotary tooling system was unacceptably high, R_a values in the order of 6 to 13 micron. The R_a values were almost 1.5 to 3 times higher than the Ra value produced when fixed circular tools were used [15]. The particle size and the volume percentage fraction exert a negative effect on surface roughness of the machined composites. An increase in the particle volume fraction also results in increased tool wear and subsequently affects the surface finish of the machined workpiece [20-23].

2.4 Tool wear

Tool life is the most important parameter for assessing machinability. Since tool life is a direct function of cutting speed, a better machinable metal is one which permits higher cutting speed for a given tool life. An important challenge in developing new tool materials is to achieve high

wear resistance while retaining the high toughness [24]. The effect of cutting tools and various cutting conditions have been studied by different researchers during turning of MMCs. Due to the presence of hard ceramic particles in the MMCs, the most of literature reported that diamond tools provide useful tool life, [2], [4] and [25-31]. In CVD coating carbide insert, TiN coated carbide inserts showed a better wear performance and also longer tool life [14], [32] and [33].
On the other hand, the effect of uncoated carbide tools and ceramic tools studied by different researchers also reported that ceramics inserts are unsuitable due to shorter tool life for machining Al –MMCs [2], [19], [25], [28], [34], and [35]. Higher cutting speeds resulted in increased cutting temperatures which led to the formation of a protective built-up layer [1], and [25]. However, considering all tested results on cutting tools, tool life is limited by excessive flank wear due to abrasion [2], [25], [28], [32], [36] and [37]. They have also observed that the absence of crater wear formation on the tool rake face is due to high toughness, high thermal conductivity and low coefficient of friction of diamond [32]. Barnes et al, studied the effect of hot machining (200 - 400°C) of MMCs and found that longer service life is influenced by Built -Up –Edges [38]. The higher volume of fraction and particle size of reinforcements resulted in rapid tool wear on the flank face of the cutting tool [2].

2.5 Shortcomings of conventional machining of metal matrix composites

Based on the available literature on conventional machining of MMC, it is observed that the reinforcement material, type, volume fraction of reinforcement and matrix properties are the factors affecting the overall machining performance of these composites. The correct selection of tooling and cutting conditions is therefore important for higher productivity and wider use in industries. Because of the expanding use of these composites and continuing problems with conventional machining, an innovative approach is needed to enhance the machining performance of such hard-to- cut composites materials.

3 Laser assisted machining

3.1 Concept of laser assisted machining

The concept of pre - heating the work piece locally prior to machining had been developed for many years, and it was only in the late 1970s that lasers emerged [39]. In recent years, many researchers utilized the concept of LAM to solve various difficulties of cutting materials [36], [37], and [39-58]. Laser assisted machining (LAM) is a hybrid method that utilizes the laser beam to ensure sufficient local heating of a workpiece prior to material removal with a traditional cutting tool. This method enables the reduction of material yield strength through the localized heating resulting in several benefits such as reduced cutting forces and tool wear, improved surface finish, higher material removal rate and reduced damage [40], [41] and [59]. The main operating parameters associated with laser assisted machining are the laser power, the diameter of the focused laser beam, the speed of the workpiece, the cut depth and feed rate. Fig. 1 shows the schematic view of a laser assisted machining setup.

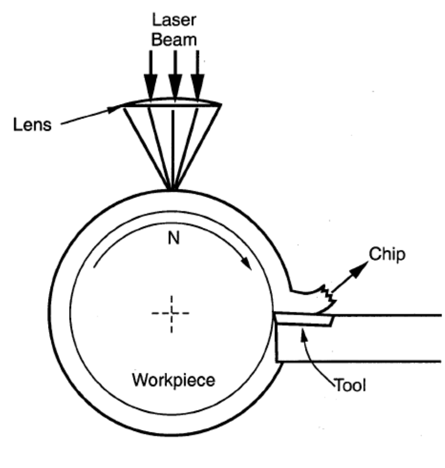

Figure1. A schematic representation of laser assisted machining [59].

3.2 Selection of laser source

Among the various types of laser sources available, CO_2 laser and Nd: YAG lasers are widely used in LAM experiments to preheat the work surface. Most of the researchers use CO_2 lasers for machining different workpiece materials because of their higher wavelength and optimal absorptivity [53], [54], [58].

However, the absorptivity has been further improved by applying coating, heat absorbing thermal paints and gas shielding so as to protect the environment from oxidation [36] and [37]. Meanwhile, Nd: YAG laser has shown a higher absorptivity on metals than ceramics [37], [41], and [43]. Irrespective of the type of the laser source used, a key success of LAM is to have a temperature control and monitoring system on the material surface during machining. This can be done through an online process temperature measurement using a suitable pyrometer: thereby it gives controls to the intensity of the laser power [43]. The selected pyrometer should be designed to measure the temperature of materials up to 2000˚C [41].

In LAM, the position between the laser beam, cutting tool (Laser lead distance), and spot diameter plays an important parameter in the intensity of the laser. Research literature reviews show that the spot diameter varies between 3.5 to 6 mm so as to reduce the damage that might be induced on the machined surface with the laser. Also the laser lead distance is reported not to be larger than 2.4 mm in order to maintain uniform temperature on the surface, [36], [42], [58], and [59]. Meanwhile, the metal matrix composites exhibit low absorptivity on the composites surface. Hence, a high power CO_2 laser source (about 1.5 kW power) was utilized on composite mixture. Chinmaya et al [58], conducted absorptivity and emissivity tests (Fig. 2) on aluminium MMC reinforced with Al_2O_3 fiber and reported that the rate of absorption on composite can be improved via graphite adhesion on the surface. However, the applied coating cannot sustain itself at high temperatures, thus there exists a temperature limit for using a CO_2 laser. This can be further improved by Nd: YAG laser without implementing coating or gas shielding techniques so that t efficiency has been increased compared to a CO_2 laser [37] and [41]. Though the Nd: YAG laser has an economic advantage over a CO_2 laser, a lack of published research work could explain weak commercialization of Nd: YAG laser for LAM. In comparison with a CO_2 laser source, Nd: YAG exhibits an even temperature distribution on the cutting surface creating in this way a favorable heat affected zone. This type of lasers have provided higher absorption rates/coefficients due to its shorter wave length and have therefore achieved a 49% of the reduction in cutting forces during LAM of Al_2O_3 fibre reinforced composite [55].

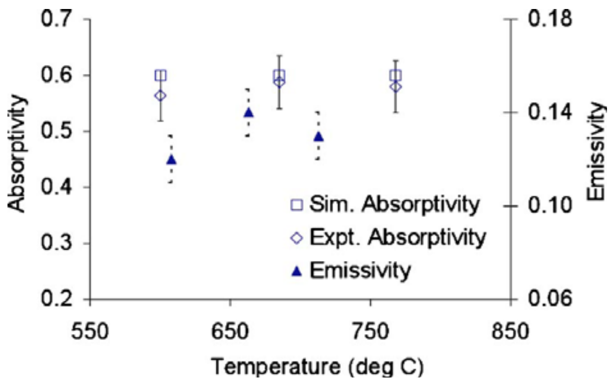

Figure 2. The effect of temperature on absorptivity and emissivity [58].

3.3 The effect of laser energy on the cutting force

The cutting force and specific cutting energy are found to be decreased with an increase in laser power or material removal temperature [49] and [50]. Y.C. Shin et al, have experimented LAM on different ceramic materials such as silicon nitride (Si_3N_4), aluminum oxide ($A1_2O_3$), partially stabilized zirconia (ZrO2) and mullite. The cutting stress at shear zone is found to drop because of increased workpiece temperature by the laser beam [44-48]. In metals, extensive studies have been carried out on Ti6Al4V, Inconel 718, hardened steel, high chromium steels and compacted graphite iron. The cutting force is found to have dropped by 20 % for AISI 4130 [51], 25% for compacted graphite iron [39], 20% on titanium alloy as compared to conventional machining [53] and [54]. However, very few studies are reported in literature on LAM of metal matrix composites. Wang et al, compared the results of laser assisted machining on Al_20_3P/Al and the conventional machining. The cutting force is found to be decreasing with an increase in the cut depth during LAM on particulate composite. However, the margin of cutting force (Fz) reduction is relatively low, i.e., 10% when compared to other two components (50%). This is brought about by softening the Al-matrix with the laser, and consecutively it becomes so soft and plastic that significant reduction in force components (Fy and Fx) has been achieved in comparison with conventional cutting [55]. Dandekar et al, experimented a 20% SiCp/Al359

MMC using carbide tools and found that the optimum material removal temperature of 300˚C and low subsurface damage are results of reduced cutting force [53].
The specific cutting energy and cutting force are reported to be decreasing with increasing laser energy or surface temperature while LAM on composite (Fig. 3). Similar results were found when employing LAM for other workpiece materials [39], [47-52]. The F_t/F_c ratio of < 1 achieved at high laser power indicates that this is the most effective material removal temperature and also proves that quasi-plastic deformation in the formation of chips has occurred during machining [53]. However, the effects of cutting speed, depth of cut and feed rate while machining these composites are to be the objects of further research.

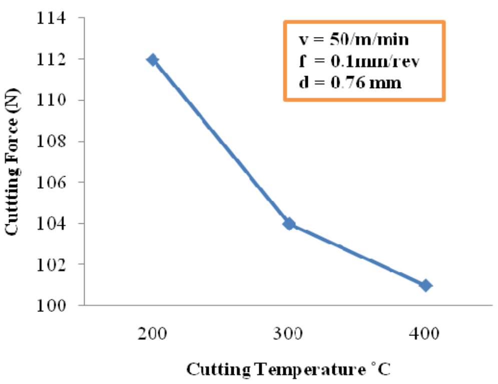

Figure 3. The effect of cutting temperature on the cutting force.

3.4 Effect of temperature on tool wear

The tool wear strongly depends on the laser power or work surface temperature. As a result of higher material removal temperature, the tool strength can be reduced and consequently the tool life decreased. Several investigations reported that there is an optimum surface temperature for every material that minimizes the flank wear and improves the tool life [51], [53], and [55]. Dandaker et al, [58] studied the effect of the laser power on tool wear during LAM of aluminum matrix composite reinforced with 62% volume fraction alumina fibers. It was reported that LAM significantly reduced the progression of tool wear with increasing surface temperature and feed respectively compared to conventional machining (Fig. 4). The author also performed experiments with the particulate composite (Al359/20% SiC) using LAM and found that the dominant tool failure mode is the result of gradual flank wear at high workpiece temperature and that this progression of flank wear has been significantly reduced with increasing workpiece temperature up to a point (300°C). Besides, a further increase in temperature has a negative influence on the reduction in tool wear. The study also reported that cutting speed has a substantial effect on tool wear as well as material removal rate. With assistance of the laser for Al/SiC with T_{mr} of 300˚C and higher cutting speed up to 100 m/min, the cutting edge was protected by a stable built up edge (BUE), which partially contributed to the reduced tool wear. However, a further increase in speed, and the presence of BUE adversely affected the surface quality of the machined composites. The reason is that the increased temperature at high cutting speeds reduced the adhesion characteristics thereby eliminating the formation of BUE [53]. LAM of 25% Al_2O_3p/Al using carbide tool results shows that the tool wear has been reduced by 20-30% more than when using conventional machining [55]. Although the cutting speed and surface temperature has a significant effect on the tool wear during machining, the effect of feed rate and the depth of cut are to be considered.

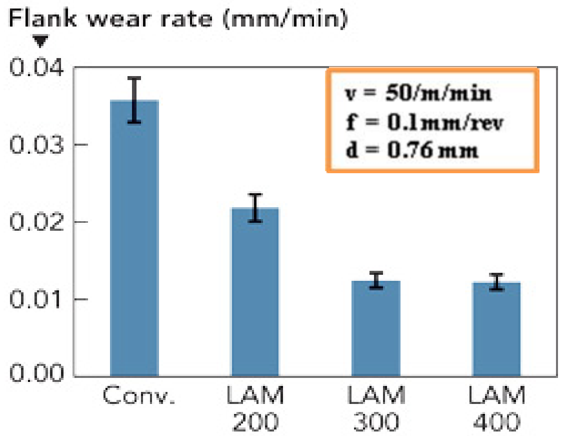

Figure 4. Tool wear vs. temperature [58].
Moreover, the reported results show that optimal conditions of machining process parameters have been established within the test conditions. Additionally, it is unclear whether these parameters are the optimum cutting parameters for extending tool life and tool wear.
It is very important to study the adverse effects on tool life imposed by the occurrence of other wear mechanisms or microstructural damage. Similar works have been reported on LAM machining of

other workpiece materials. Shuting et al, observed an improved tool life of 42 min at T_{mr} of 1410˚C on cutting Silicon Nitride with PCBN tool. There is an evidence of dominant failure mode brought about by adhesive interface resulting in tearing the cutting tool material and consequently tool wear [47], [50] and [56].

3.5 Effect of cutting parameters on surface quality

The surface quality of a machined component was demonstrated by measuring the surface roughness and surface/sub surface damage. Many research works have been reported in literature on surface roughness; surface/subsurface quality for LAM of ceramics, metals and ferrous alloys. However, very few studies are available on the composite material. Dandekar et al, reported the work on LAM machining of Al_2O_3 fibre reinforced composites and found the variation of surface roughness with respect to workpiece temperature. The results are depicted in Fig. 5. Surface roughness has been significantly reduced (65%) in LAM up to surface temperature of 300°C, in comparison with conventional machining [58]. Beyond 300°C, debonding between the fiber and the matrix, micro cracking of fibers and fiber pullout is observed, and this has resulted in a slight deterioration of surface quality. The subsurface damage depth after a laser assisted turning process shows less fiber damage. The damage depths are 167–157 µm with assistance of the laser, and these are smaller than those of 137–125 µm performed by using conventional turning at the same cutting conditions.
However, the experiment performed on the particulate composites shows that the surface damage is independent of surface temperature and that it depends on the particle size [53]. The effect of cutting speed and rake angle on subsurface damage for the machined long fiber MMC was compared to that of conventional machining. At low cutting speed and large rake angle, the higher surface roughness and minimum sub surface damage rate have been produced, which was controlled by minimum particle fracture or fiber pull-out rates. Compressive residual stress is observed on the laser assisted machined surface of Al_20_3/A1 and the magnitude of residual stress has been increased 3 times by conventional machining. The reason is that the softened matrix is easily squeezed out from the machined surface, while Al_2O_3 particle is pushed in from the machined surface, thus producing a higher concentration of Al_2O_3 particles in the surface layer and increasing the wear resistance of the machined surface [55]. This has resulted in an improved surface finish.

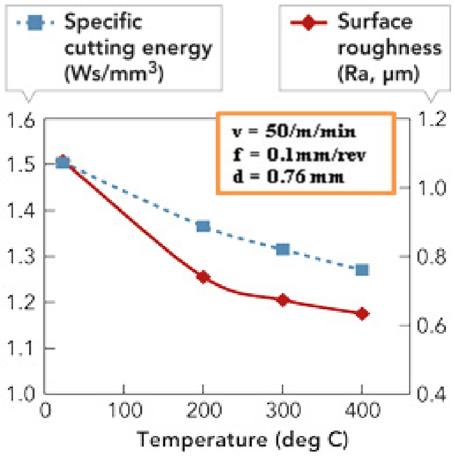

Figure 5. The Effect of temperature exerted on Specific cutting energy and surface roughness [58].

3.6 Chip morphology during LAM

Due to high hardness and brittleness in nature, the formation of chips during machining of brittle material does not occur by plastic deformation. But the strength and brittleness can be reduced at elevated temperature; thereby the material is removed by both brittle fracture and plastic deformation. A multi- scale finite element modeling of LAM of fibre and particulate reinforced MMC was developed by Dandekar and Shin [57] to study the sub-surface damage in terms of particle fracture, matrix void formation and debonding depth. The result showed that micro cracks initiated and propagated under the loading of tool at material removal temperature of 300˚ C. The micro cracks propagated and coalesced into a macro crack in the shear zone, which produced a sharp decrease in main cutting force. There is a lack of a detailed study on the chip formation and its mechanism for composite material under LAM conditions.
The types of chips produced in conventional machining and LAM could prove to be essential in predicting tool wear and surface damage.

3.7 Modeling and optimization

Advantages of LAM over conventional machining have attracted some research into the improvement of machinability for difficult-to-cut materials [45-53]. Only few studies with reference to the optimum levels of LAM parameters for achieving improved machinability have been systematically investigated via minimum cutting force, better surface finish, higher material removal rate and tool wear. However, the optimal value of LAM parameters depends on both laser parameters and machining parameters. It is difficult to find the optimal machining parameters due to the complexity of influence parameters and their interaction effects. The Ishikawa cause and effect diagram shown in Fig. 6 depicts various process parameters for defining optimal or near-optimal cutting conditions during LAM. A statistical design of experiments is to be utilized to investigate the effect of LAM parameters on machining performance and to predict the optimal parameter setting. Dandekar et al, proposed a multi-step 3-D FEM simulation model for prediction of cutting forces and induced sub-surface damage in an A359/SiC/20p composite [57]. Usually, a machining process is often characterized by a group of responses. If more than one response comes into consideration, it is very difficult to select the optimal setting for meeting all quality requirements simultaneously. Otherwise, optimizing one quality feature may lead to severe quality loss or other quality characteristics which may not be accepted. Hence, simultaneous optimization approach can be implemented in LAM process. Further fuzzy logic, artificial neural network and regression techniques could be used for modeling the LAM process and analyzing the performances.

4 Summary and outlook

This paper gives a survey of the thorough literature so as to understand the complex mechanism of machining MMCs by conventional method and laser assisted machining. LAM proved the benefits of improved machinability and higher productivity when compared to conventional machining. The review of available literature shows that LAM of metal matrix composites is mainly focused on experimental investigation into the process characteristics and its benefits. The following are the general conclusions that can be drawn for LAM of MMCs. Laser power and surface temperature are the most influential factors on the process characteristics.

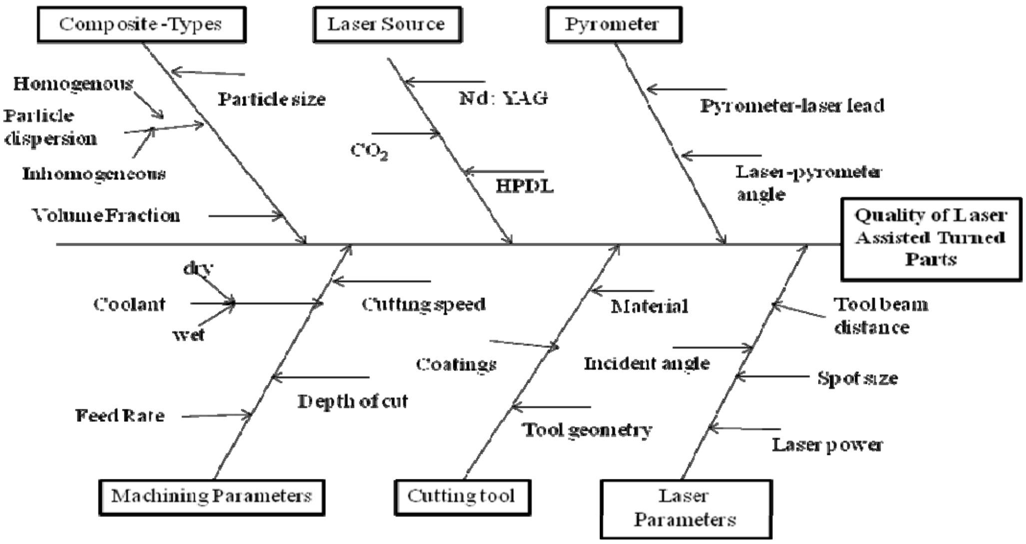

Figure 6. Ishikawa cause-effect diagram of a laser assisted turning process.

The preliminary experiments are required to determine the optimal temperature range for the suitability of material characteristics. According to the selection of heat source location and thermal conductivity of the material, processing depth and cutting speed can be selected. Taguchi based experimental design and modeling is of great importance to a better process understanding and process optimization. As there is a lack of a complete study on optimization of cutting conditions and laser parameters in the published work, these aspects could be considered in future research.

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