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Laser Assisted Machining of difficult to cut materials: Research Opportunities and Future Directions - A comprehensive review

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Abstract

High strength alloys such as nickel and titanium and advanced engineering materials such as ceramics, composites are being developed and widely used in aerospace, automotive, medical and nuclear industries due its inherent physical-mechanical properties. However conversion these new materials into engineering products are always associated with machining. The machinability characteristics such as higher cutting force, higher cutting temperature, poor surface integrity and shorter tool life associated with these materials posing many challenges to the researchers, and hence considered as difficult to cut materials. Conventional methods of machining these materials are found to be uneconomical. In recent days, many attempts have been made to improve the machinability of these materials more effectively via use of external energy assisted machining. Among the various external energy assisted machining methods, laser assisted machining (LAM) has received the attention of researchers in the metal cutting domain and a few research was carried during the recent years. This paper is aimed to review and summarize the potential use of LAM for difficult to cut materials, current progress, benefits and challenges in laser assisted machining. In addition an optimization frame work to study the effect of laser parameters and machining process parameters on machinability performance is not reported which is applicable to industrial processes It is concluded that further experimental modeling and empirical techniques are required to create a predictive based models that gives good agreement with reliable experiments, while explaining the effects of many parameters, for machining of these difficult-to-cut materials.

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Keywords: Laser assisted machining; difficult-to-cut material; Laser parameters; Machining parameters

1. Introduction

In recent decades, advanced materials such as titanium and nickel based super alloys, ferrous alloys, ceramics, composites and cobalt-chromium alloys are being developed for high strength and heat resistant applications which includes automotive, aerospace, nuclear, medical and electronic industries [1,10].

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These materials are characterized with excellent strength-to-weight ratio, strong corrosion resistance and ability to retain high strength at high temperature. These materials all have superior strength and toughness compared to conventional, engineering material. However, applications of these materials are not growing currently because which makes half of the final cost of the product for converting a final component [1, 2]. This is attributed to low cutting speed, smaller depth of cut due to excessive tool wear. Therefore these materials are considered as difficult-to-cut materials. Many problems are encountered during machining such as excessive heat generation in cutting zone and high friction between tool-chip interface, tendency for BUE formation and catastrophic failure of cutting edge [3,4,5]. This could have a significant effect of machining process performances such as poor machinability, high machining cost and low productivity. Because of the inherent characteristics of difficult-to-cut material, conventional machining methods such as milling or turning are proving inefficient. A number of innovative machining processes like abrasive machining, laser machining, electrical discharge machining, chemical machining, thermally-assisted-machining methods such as laser assisted machining, plasma assisted machining are currently being applied to these materials. Among the many approaches one approach, which is becoming increasingly popular with difficult-to-machine materials, is laser assisted machining (LAM) due to its higher benefits, substantial growth in technology and to the commercial viability. In this context, this paper highlights the current progress and challenges in LAM in relation with the effect of laser parameters and machining parameters on process efficiency of difficult-to-cut materials.

2. Laser Assisted Machining – Overview

Laser assisted machining is a hybrid method which uses a high power laser to locally heat the workpiece prior to material removal with a traditional cutting tool. At elevated temperatures the yield strength of a brittle material decreases to below the fracture strength changing the material deformation behavior from brittle to ductile. Also at elevated temperatures, the yield strength of strong, ductile material decreases, thus reducing cutting forces and tool wear as well as improving surface quality [6]. Figure 1 shows a schematic of laser assisted machining.

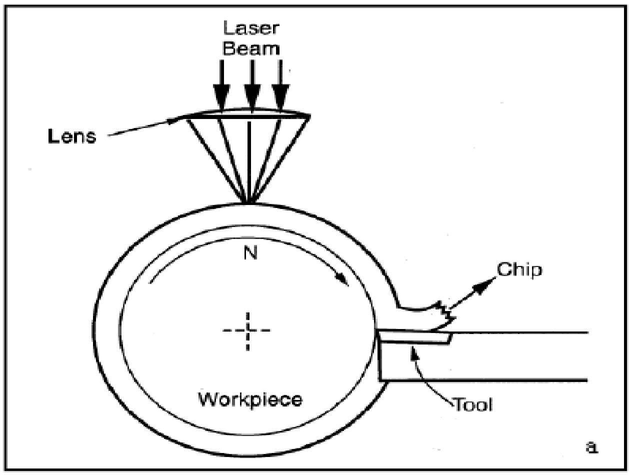

Fig.1. Schematic setup of Laser Assisted Machining [2]

Two main laser sources are widely used in LAM experiments are CO_2 laser and Nd:YAG laser. The latter, having a shorter wavelength, has better absorptivity. CO_2 laser has less beneficial on most of the difficult to cut materials such as Inconel, hardened steel and composite materials when compared to Nd: YAG due to low absorptivity of laser energy [7,8,9]. Most of the research has been focused on the benefits of LAM and addressed the challenges in conventional machining. But, the machining results of LAM depend on both machining process parameters and laser parameters. The main operating parameters associated with laser assisted machining are: Laser power, spot diameter of the laser beam, cutting speed, feed rate and depth of cut. The optimal setting for LAM is difficult due to the many control parameters and their interactions. In addition, a statistical study based on design of experiments is needed to be investigating the effect of optimal LAM parameter and their interactions is lacked in publication.

3. Effect of Laser parameters and machining parameters on difficult to machine materials

Recently, LAM has identified an important area of research and applied to many high strength and high hardness materials. To realize the maximum benefits of LAM, one needs to understand the interaction effect of laser process parameters on different work piece material and the optimum levels to achieve lower cutting force, low machining cost and surface quality [7]. Workpiece surface temperature, cutting speed, feed rate, depth cut, the laser spot diameter, laser-tool lead distance, focal length has play a significant roles in LAM process in order to avoid surface damage and premature failure of cutting tools. In this section, the effect laser parameters together with machining parameters on different difficult –to-cut materials are reviewed.

3.1Titanium alloys

Titanium alloys are attractive materials in aerospace, automotive, biomedical, nuclear and gas turbines industries due its superior physical-mechanical properties such as excellent strength-to-weight ratio, strong corrosion resistance and ability to retain high strength at high temperature [10,11,12]. These properties together with low modulus of elasticity, low thermal conductivity, high strength and hardness at elevated temperature and chemical reactivity with cutting tools makes machining these material extremely difficult resulting in shorter tool life [10]. Lower cutting speed and shorter tool life which leads higher machining cost for these alloys [11]. Some research attempts have been made to analyze the machinability via dry, cryogenic assisted machining to increase cutting speed and tool life. Studies reveal that cryogenic assisted machining gives substantial improvement in tool life compared to dry machining [12]. The combination of low feed /high depth of cut improves the tool life by 6 times when compared to high feed/ low depth of cut at constant cutting speed of 125 m/min with use of liquid nitrogen as a coolant [13,14]. Due to substantial growth of Laser assisted machining is addressed to improve the machinability of titanium [7,8]. At higher cutting speed, LAM resulted in shorter tool life due to diffusion wear at material removal temperature of 250˚C temperature compared to conventional machining [15]. However, LAM benefits on these alloy via hybrid machining i.e LAM in cryogenic machining [15] and reported the maximum tool life, in terms of MRR due to lower tool-chip interface temperature, lower friction between the cutting tool and workpiece. It was observed that TiAlN coated carbide cutting inserts yield an overall saving of tool life during LAM and hybrid machining [15].

Further research was taken on benefits of uncoated carbide cutting inserts with cryogenic coolants for investigating the tool life and wear mechanism when turning of Ti-6Al-4V at high speed (125 m/min). The result reveals that the machining with coolants significantly improves the tool life by 235% compared to LAM alone and it was found that coolant suppress the adhesion, diffusion wear which significantly improves tool life [16]. However, the researchers are focused on the potential of LAM in industrial application by critical analysis of the effect of laser beam on cutting force and cutting temperature and resulted a significant reduction in cutting force (15%)[17]. It was observed that with increasing of laser energy (between 1200 W- 1600 W and laser beam spot size of 2-3mm), there is a >10% reduction in cutting force is observed in cutting speed range of 25 – 125 m/min and also observed a shorter tool life at cutting speed >150 m/min. The chip morphology study on LAM reveals that the chip formation is strongly depending on cutting speed and laser power [18]. It was observed that at constant laser energy, the change from saw-tooth to continuous chip and back to saw-tooth at higher cutting speed. Table 1 summarized the latest researches in laser assisted machining of Titanium alloys.

3.2 Nickel based alloys

Nickel based alloys such as Inconel, Hastelloys, Waspaloys and Udimet are another attractive materials over titanium alloys used in aerospace and nuclear industries such as gas turbines, jet engines and thrust reservoir due to chemical and mechanical properties at elevated temperature [10]. Due to high temperature at cutting zone at

Table 1 Summary of Laser assisted Machining of Titanium alloys

Process	Author	Process parameter	Performance Measures	Remarks
Dry machining	Sun et al. (2009)	Speed, feed rate and depth of cut	Cyclic force, Cutting force and chip formation	The cyclic force and length of undeformed surface in the segmented chip increase with increase in feed rate and independent of depth of cut and cutting speed. The cutting force increased with increase feed rate and depth of cut. The cutting force decrease with cutting speed due to two phase of strain hardening. This limits the machining speed and productivity.
Cryogenic Assisted Machining	Berminghа m et al (2011)	Feed rate and depth of cut at constant speed and material removal rate (125 m/min, 48.5 cm3/min),	Tool life	The results show that low feed rate and high depth of cut improved the tool life by 6 times compared to high fed rate and low depth. It also shows that it is necessary to select correct combination of feed rate and depth of cut is more important for extending tool life rather than selection of inefficient cutting parameters with cryogenic cooling strategy.
Hybrid machining	Chinmaya et al. (2010)	Speed	Cutting force, specific cutting energy, surface roughness, microstructure and tool wear	The results show that it is possible to increase the machining speed via LAM and hybrid machining. It also possible for obtaining minimum cutting force, improved tool life and reasonably good MRR
Laser Assisted Machining, High pressure coolant, cryogenic coolant	Berminghа m et al (2012)	Speed, feed rate, depth of cut and enter angle	Tool Life and Wear Mechanism	The result shows that the LAM improves the tool life by 7% compared to 235% improvement occurs when coolants are used under identical experimental conditions
Laser Assisted Machining	Rahman et al (2012)	Speed, feed rate, depth of cut, constant laser power and spot size	Cutting force and cutting temperature	The results shows that is it possible to select the optimum cutting parameter for obtaining minimum cutting force and cutting temperature.
Laser Assisted Machining	Rahman et al (2012)	Laser power	Cutting force	The obtained results indicated that the laser power has significant on cutting force. The increasing the laser power from 1.2 kW to 1.6 kW resulted in an extension of the beneficial cutting speed range from 25 m/min – 125 m/min

1200˚C, chemical reactivity with most cutting tools and presence of hard abrasive particle such as TiC, CrC, MoC in microstructure which makes the machining of this alloys difficult and encourages the abrasive wear. This results in low cutting speed, shorter tool life, poor surface quality and thus high machining cost [19,20].

In recent years, LAM was utilized to improve the machinability on nickel based alloys. As the hardness of Inconel is deceased rapidly above 600˚C -700˚C and therefore the material removal temperature (Tmr) of the work piece material need not be elevated unlike in LAM of ceramics. Due to low absorptivity on metals, a high power laser was utilized on Inconel 718 at early stages [19]. The Anderson et al, reported that rate of absorptivity on

Inconel 718 can be improved via graphite adhesive on surface for CO_2 laser and results are proven. However, the applied coating cannot sustain itself at high temperature and multiple laser units are used simultaneously on the unturned surface and chamfer surface to improve the machinability [20]. High power laser energy, small laser beam diameter, smaller feed rate and larger preheating time could resulted in required Tmr on work piece [21]. On other hand, along with Tmr, feed rate has the highest influence factor on specific cutting energy. As laser energy heats the material surface to 540˚C for Inconel 718 [20] and in between 300-400˚C for Waspaloy [23], the average flank wear and notch wear decreased with increasing speed from 60 m/min to 180 m/min for Inconel 718 and for Waspaloy.

The integrity of machined surface (roughness, surface/sub-surface damage, residual stress, micro hardness), in particular surface roughness is improved slightly with the use of ceramics inserts in LAM over conventional machining [22]. A comparative analysis of ceramic and carbide inserts using LAM is experimented and resulted that life of uncoated carbide insert is less compared to conventional machining [22]. Further experiments carried with Sailon cutting tool and reported that surface roughness improved by 25% for ceramic tool which yielded the favourable result in spite of the previous research associated with poor surface quality [21]. Furthermore, the LAM produced remarkable increase in material removal rate. The Sailon ceramic tool demonstrated 800% increase in material removal rate and 50% improved tool life compared to conventional machining. Table 2 summarized the latest researches in laser assisted machining of Nickel based alloys.

Table 2 Summary of Laser assisted Machining of Nickel based super alloys

Author	Process parameter	Performance Measures	Remarks
Rajagopal et al. (1982)	Beam orientation and surface coating	Cutting force, economic viability	Due to inefficiency of laser material interaction and low absorptivity of metals, interest of LAM is diverted. A coating is often required to enhance the rate of absorptivity on metals in order to increase the process efficiency.
Anderson et al (2006)	Surface coating, feed rate, speed	Process efficiency	The results shows that a high absorptivity of CO_2 laser energy in metals by selecting a suitable coating conditions and an approximate absorptivity value of 0.80 was determined through a systematic approach which is missing previously.
		Multiple laser units (CO2 and Nd:YAG laser source):	As the applied coatings cannot withstand very high temperatures, thus there exists a temperature limit when using a CO_2 laser. The author developed a two laser setup to create the desired temperature distribution in the work piece.
		Machinability benefits	It is observed that the cutting speed has the most significant influence on specific cutting energy, surface roughness and tool wear followed by feed rate and depth of cut.
Germain et al (2008)	Cutting parameters, type of inserts	Residual stress	The obtained result indicated that tensile residual stress is observed in axial and tangential directions and this magnitude is smaller than conventional machining only in the axial direction when machining with carbide tools.
		Tool life and surface integrity	Compared to conventional machining, the LAM showed marginally results in terms of the surface roughness and tool life with ceramic inserts
Attia et al 2010)	Speed, feed rate, depth of cut	MRR, surface finish	LAM, using the ceramic tool under the given conditions, yielded the most favourable results despite previous research associating ceramic tools with poor surface quality.

3.3 Ceramics

Advanced structural ceramics such as mullite, Zirconia, alumina and silicon nitride is identified as another attractive material due to its compressive properties [24,26,27,28]. Due to their low density, superior wear resistance, and high temperature strength, these are usually employed in the manufacture of critical components in automotive and aerospace. Most past research into LAM has been carried out on this material because of their hardness and brittleness [24, 25]. It was found that PCBN cutting tool shows a longer tool (say 121 min) when LAM on zirconia at a Tmr of 900 ˚C -1100˚C [27] and a carbide insert has been used for LAM on alumina at 850˚C [29] and mullite (say 44 min) [28]. Three dominant wear mechanisms such as abrasion, adhesion and diffusion is attributed for tool wear and strongly depend on material removal temperature [27]. Therefore, it is necessary to find the optimal material removal temperature for the longer tool life [26]. However, finding the optimal Tmr is difficult due to complexity of influence parameters and their mutual interactions.

The cutting force and specific cutting energy are found to decrease with increase surface temperature with laser energy when LAM on ceramics but not significantly influence by laser tool lead distance [25,27,28]. The influence of cutting speed on cutting force is insignificant but otherwise feed rate [28,29]. The force ratio such as feed force/cutting force is found to decrease on zirconia [28] and mullite [29] resulted at higher Tmr which indicates the evidence of significant softening of the work piece near the cutting zone and quasi-plastic deformation. It is observed that cutting speed has the most significant influence on surface roughness followed by feed rate and depth cut [30].

When examine the chip morphology, it was found that material removal temperature and force ratio (Ff/Fc < 1) plays a key role during chip formation compared to other parameters [25,26]. For the workpiece temperature in the range of 1260˚C-1410˚C, based on the SEM investigation of chip obtained, Lei [25] observed that plastic deformation of silicon nitride in the shear zone was continued by the enhanced mobility of the rod-like silicon grains which is facilitated by a reduction in the viscosity of inter granular glassy phase at the higher temperature.

For mullite, Patrick developed a double-ramp laser experimental setup to prevent the thermal fracture of the work piece because of low thermal diffusivity, fracture toughness and tensile strength of the porous material, in comparison to silicon nitride [28] and inferred in three different mechanism such as brittle fracture and semi continuous chip for (Ff/Fc >1) and operating working temperature window of 800˚C-1000 ˚C to continuous chip formation for (Ff/Fc <1) and operating working temperature window greater than 1300˚C. This sign is not observed when LAM on zirconia [28], but plastic deformation occurs during chip formation along with brittle fracture. The surface roughness, is not sensitivity to material removal temperature during LAM of silicon nitride [25] but it depends on size and distribution of silicon nitride grains and for zirconia [25,27]. Local cracks are presented on heat affected zone prior material processes and remains in the subsurface when its thickness of cracking is greater than depth of cut [27]. Therefore, it is necessary to control the material removal temperature to produce crack free surface during LAM. Table 3 summarized the latest researches in laser assisted machining of ceramics.

3.4 Ferrous alloys

Low carbon ductile steels, stainless steel and hardened steel have been classified under iron based difficult to machine material and found its application in automotive such as gears, cranks shafts and engine blocks [10]. However, machining of these automotive components presents a major problem, due to high hardness and fracture toughness with the traditional machining technology [31]. The concept of hard turning technique is referred for these steel whose hardness beyond 45 HRC. This technique eliminates the secondary process such as grinding and heat treatment which contribute up to 60-90% of the final cost of the machined product [33]. However, an experimental investigation using LAM have been carried out on AISI D2 steel [31], compacted graphite iron [32], AISI 4130 steel [33], high chromium white cast iron [34] and XC42 steel [35], in order to reduce the overall machining cost and to increase the productivity through a replacement of grinding process and hard turning.

Table 3 Summary of Laser assisted Machining of Ceramics

Author/year	Process parameter	Performance Measures	Remarks
Sutting et al. (2000)	Laser power and preheating time	Material removal mechanism, shear zone stress	The results show that the deformation behaviour can be evaluated by the constitutive model. The average relative error falls within 20% of the experimental values.
Lei et al (2001)	Laser power and preheating time	Tool wear	The severity of material deposition on cutting tool can be minimized by maintaining optimum cutting zone temperature.
		Material removal mechanism	Due to softening of glassy phase material, the material removal is achieved through a combination brittle fracture and plastic deformation
		Surface integrity, surface/subsurface damage	It is observed that surface roughness strongly depend on size and distribution of the silicon nitride, but not significant affected by Tmr. No evidence of surface/subsurface crack on the machined surface.
Patrick et al (2002)	Laser power, beam diameter, laser-tool distance, speed, feed rate, depth of cut	Cutting force, surface roughness, chip morphology, tool wear	The results show that optimal conditions of machining process parameters are established within the test matrix.
Patrick et al (2004)	Laser source	Tmr	Developed a double-ramp laser source for LAM on work piece to prelude thermal facture of the work piece due to low thermal diffusivity, facture toughness and tensile strength than silicon nitride
Chih-Wei Chang et al (2007)	Speed, feed rate, depth of cut, pulsed frequency	Surface roughness	The results confirm that the efficiency of Taguchi approach employed for the optimization of process parameters in this study.
Frank et al (2010)	Speed, feed rate, depth of cut, laser power, Tmr	Specific cutting energy, force ratio, Tool wear, surface integrity	The results show that it is possible to select the optimal value of material temperature at a level for the selected range within the test matrix for obtaining minimum cutting energy and surface roughness.
Jong-Do Kim (2011)	Laser power, feed rate, depth of cut	Cutting force, tool life	Due the running cost of a diode laser is cheaper than a CO2 laser and it is employed for machining of silicon carbide. The results shows that feed rate and depth of cut have negative effect of cutting force and tool life.

It is observed that the laser tool distance has the most significant influence on the cutting force during machining of hardened XC42 steel than the conventional cutting method with the largest reduction of 65 % for the radial, cutting force and 85% for the feed force [35]. Experiment results confirmed that laser tool distance is a critical factor in the success of laser-assisted machining [34]. This is because the temperature at surface drops as the distance between laser spot and cutting tool increase and take more time to dissipate the heat into the work piece.

In LAM of AISI D2 steel not only the magnitude of thrust force is reduced, but also amplitude variation of cutting force is reduced which is attributed to the greater reduction of machine vibration. This is due to longer duration of heating cycle and distribution of laser beam [31]. Preheating temperature when LAM of compacted graphite iron is most significantly affected by laser power and feed rate [33]. It is found that with assistance of laser heat, the flank wear and catastrophic failure of the carbide tools is reduced and improved tool life by as much as 100 % for LAM of D2 steel [31], because of the softening the workpiece around 300˚C-400˚C for the uncut chip thickness of 0.05mm and a stable BUE which protects the cutting edge during LAM. However, the tool life when machining compacted graphite iron is significantly affected by feed rate [32] In LAM of hardened steels, residual stresses become more compressive and the stress penetration depth becomes smaller when compared to conventional cutting [33]. Unlike titanium alloy, the chip morphology changes form saw tooth chip to continuous chip when LAM of D2 steel due to higher surface temperature [31]. The formation of saw-tooth chip in machining is one of the primary causes of chatter and found that preheating the workpiece in LAM results in a dramatic reduction in the amplitude vibration and chatter [31,32] . Table 4 summarized the latest researches in laser assisted machining of ferrous alloys.

Table 4 Summary of Laser assisted Machining of ferrous alloys

Author/year	Process parameter	Performance Measures	Remarks
Dumitrescu et al. (2006)	Higher power diode laser in longitudinal and orthogonal turning process	Tool life, chip formation, cutting force	The results show that the improved tool life and surface finish, surface of machine chatter and saw tooth chip formation.
Skvarenina et al (2006)	Feed rate, speed	Tool wear, surface roughness, cutting force, specific cutting energy, production cost	It is observed that results is focused on the feasibility and machinability of LAM on CGI wherein higher MRR and longer tool life are obtained by optimizing the laser parameters
Hongtao Ding et al (2002)	Speed, feed rate, depth of cut, laser power, preheating time.	Surface finish and residual stress	Reported that the surface finish and residual stress produced by LAM, wherein the surface roughness Ra is about 0.34 µm for small feed rate 0.05 mm/rev, residual stress become compressive and the stress penetration depth becomes deeper when compared to conventional machining.
Masood et al (2011)	Laser-tool distance	Cutting force, cutting chips	The results shows that moving the laser spot closer to cutting tool reduces process forces and confirming the laser-tool distance is a critical factor for the beneficial of LAM.

3.5 Composite

Composites are inhomogeneous in nature usually formed by dispersing of particles, fibre and whiskers in a matrix. Incorporation of hard reinforce particle/fibre enhances the properties like adhesive, abrasive, diffusion wear resistance, thermal properties, hardness, and stiffness. The inherent challenge of machining of these composites is excessive tool wear and subsequent damage in the work piece. Poor machinability is because of fibre pullout, delamination, uncut fibres, high dimensional deviation, and high surface roughness [10].

Softening of the Al-matrix by the laser energy, which become softer and plastic, leads to significant reduction in force components when compared to conventional machining. Based on microscopic analysis, the Wang [36] inferred that the softened matrix is easily is squeezed out from the machined surface while Al_2O_3 particle is pushed in from the machined surface, which leads to higher concentration (37%) of Al_2O_3 particles in the surface layer increase the wear resistance of the machined surface. This resulted in improved surface finish and longer tool life. Higher compressive residual stress (3 times than conventional machining) is reported with LAM. However, Barnes et al, studied the effect of hot machining (200 - 400°C) of Al/SiCp/18P MMCs and found the increased tool life due to built up edges at low cutting speed [37]. But at higher work piece temperature, the composite bar exhibit shorter tool life than conventional machining.

Further research on particulate MMCs (Al/SiCp/20) was carried to study effect of workpiece temperature together with different range of cutting speed (at both lower and higher cutting speed) and the results are indicated that the surface roughness (37%), tool life (40% at 150-200m/min compared to 57% at 50-100m/min) and the damage depth are dependent on cutting speed over conventional machining by defining the surface roughness criteria as 2 μm [3]. The effect of workpiece temperature on subsurface damage is relatively independent due to small range of Ft/Fc. However, LAM on $Al/Al_2O_3/60f$ shows observable damage in terms of fibre pull out is decreases with increasing material removal temperature. Feed rate has negative effect on tool life and surface roughness along with material removal temperature of 300˚C [39]. Table 5 summarized the latest researches in laser assisted machining of composites.

Table 5 Summary of Laser assisted Machining of Composites

Author	Process parameter	Performance Measures	Remarks
Wang et al. (2002)	Speed, feed rate, depth of cut	Cutting force, tool wear , tool life, residual	The results show that the improved tool life and surface finish due to ductile manner of deformation which reduces the friction forces acting on the cutting tool.
Chinmaya et al (2012)	Speed, Tmr	Cutting force, specific cutting energy, surface roughness, subsurface damage and tool wear	The results shown that LAM is consistently outperformed at all cutting speed in terms of machinability benefits compare to conventional machining when suing the surface roughness (Ra=2μm) as a metric efficiency.
Chinmaya et al (2012)	Speed, Tmr	Cutting force, specific cutting energy, surface roughness, subsurface damage and tool wear	Cohesive Zone model have been employed to find the damage prediction as a function of Tmr and compared with experimental data. it is observed that debonding depth and fibre damage significantly affect by cutting speed and larger tool angle followed by feed rate.

3.6 Cutting tool materials employed in difficult to machine materials

The inherent challenge during machining of these difficult-to-materials is that the selected cutting tool should withstand the mechanical and thermal stresses at high temperature. The different types of cutting tools, ceramics, coated carbide inserts, CBN, PCD, PCBN are employed in LAM. PCBN is used for LAM of silicon nitride [25] and Zirconia [27], carbide insert for alumina [29] and mullite [28]. However, the longer tool life is observed in PCBN compared to carbide when LAM of Zirconia at the test conditions. The most common wear mechanism observed on laser assisted machining of zirconia with PCBN is abrasion, diffusion and adhesion [27]. But the abrasive and diffusive wear is not observed in LAM of silicon nitride [25,30] when compared to zirconia [27] due to low ductility and thermal diffusivity of zirconia. PCD is found to be not suitable for LAM on zirconia ceramics. Based on the research conducted and investigated on different types of cutting tools Ti-6AL-4V [15] and Inconel 718 alloys [20], reported that TiAlN coated carbide inserts is the most appropriate tool for LAM for surface roughness improvement. Ceramic insets are considered as an alternative tool for machining of nickel based alloys [10, 22] for higher tool life and but it is not suitable for titanium alloys due to chemical reactivity, poor thermal conductivity and low toughness. Carbide inserts SPG 422 by Kennametal K68 [31] either TiN coated or uncoated type cutting inserts are used of cutting of hardened steel and composites. In case of LAM of composites, the carbide inserts are used for favourable results in terms of material removal rate, improved surface integrity and longer tool life at higher cutting speed [38, 39].

4. Scope for optimization of LAM Process

Advantages of LAM over conventional machining attracted many researches on the improvement of feasibility and machinability benefits difficult-to-cut material. Few studies have been systematically investigated to select the optimum value of LAM parameter for obtaining minimum cutting force, reasonably good MRR and effect of type of cutting tool materials on the wear mechanism. 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. This review focused to characterize the laser assisted machining process by identifying how individual parameter affects the machining results. Due to the complexity, a statically based design of experiments is need to investigate the effect of laser parameters on machining results and their mutual interactions effect to predict the optimal LAM parameter setting. Usually performance of a machining process often characterized by a group of responses. If more than one response comes into consideration it is very difficult to select the optimal setting which can achieve all quality requirements simultaneously. Otherwise optimizing one quality feature may lead severe quality loss to other quality characteristics which may not be accepted. Hence simultaneous optimization approach can be implemented in LAM process.

5. Conclusion

In this study, an attempt has been made to the detailed review of laser assisted machining of difficult-to-cut materials. The review results are summarized as follows:

1. It is evident that the Laser assisted machining can be used to increase the process efficiency of materials with difficult-to- cut when compared to conventional methods.
2. However, still further more research in this area is required to have good understanding of process-material removal mechanism and to select the process parameter in the proper way.
3. Simulation based models need to be developed to analyze the temperature distribution into material, which is necessary to reduce the mechanical strength.
4. The studies are reported only the one parametric effect on machining of these difficult to cut materials. However, simultaneous influence on variation factors on obtaining favorable machining studies has not been explored well in a comprehensive way.
5. Further research needs to be conducted on the optimal selection of process parameters of beam size, laser power, cutting parameter like cutting speed, feed rate, depth of cut, and other factors for achieving overall productivity. Current research interests include also exploring the effects of simultaneous influence of machining parameters by means of experimental and empirical methods.
6. Most of the recent researches on LAM have been largely focused on laser assisted turning. However, other machining processes like milling, drilling and grinding play a vital role in production systems.

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