

Laser assisted machining: a state of art review

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Laser assisted machining: a state of art review

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Abstract. Difficult-to-cut materials have increasing demand in aerospace and automobile industries due to their high yield stress, high strength to weight ratio, high toughness, high wear resistance, high creep, high corrosion resistivity, ability to retain high strength at high temperature, etc. The machinability of these advanced materials, using conventional methods of machining is typical due to the high temperature and pressure at the cutting zone and tool and properties such as low thermal conductivity, high cutting forces and cutting temperatures makes the materials difficult to machine. Laser assisted machining (LAM) is a new and innovative technique for machining the difficult-to-cut materials. This paper deals with a review on the advances in lasers, tools and the mechanism of machining using LAM and their effects.

1. Introduction

The use of high strength materials like titanium alloys, nickel alloys, and tool steels, in industry is increasing [1]. They are still being researched and developed to meet the increasing requirement of higher strength and heat resistance especially in the aerospace industry [2] [3]. The machinability of these advanced materials is typical due to the high temperature and pressure at the cutting zone and tool. Properties such as low thermal conductivity, high cutting forces and cutting temperatures makes the materials difficult to machine. Thus introduced a new processing method called as thermally assisted machining (TAM). Thermal assisted machining includes Gas torch, Induction and Furnace preheating method, Plasma assisted machining, and Laser assisted machining [4].

The difficult-to-cut materials have good characteristics, but they are difficult to machine using conventional machines because of their physical and chemical characteristics such as brittleness [5]. Laser assisted machining is a new and innovative technique for machining the hard-to-wear materials. Laser is used as a heat source with the beam focused on the un-machined section of the work piece to soften the material directly in front of the cutting tool. The addition of heat softens the surface layer of the material, so that ductile deformation rather than brittle deformation occurs during cutting [6]. Most important advantage of laser assisted machining is its ability to produce much better workpiece surface quality than the conventional machining, together with larger material removal rates and moderate tool wear [7]. LAM is gaining more popularity for their high laser beam intensity at low mean beam power, good focusing characteristics due to very small pulse duration, small kerf widths and narrow heat effected zones, high productivity, reduced process, eco-friendliness, low manufacturing cost and better surface finish [8].



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2. Hard-to-cut material

In recent years, the use of difficult-to-cut materials has increased the development of automobile, aerospace, shipbuilding and semiconductor industries, as they have much better high temperature strength, durability and corrosiveness than general metal [9] [10] [11] [12]. Difficult-to-cut materials include titanium alloy (Ti-6Al-4V alloy) [13], nickel-based superalloy (Inconel 718 alloy) [14], compacted graphite iron [15], mullite [16], Si_3N_4 ceramic [17] [18] [19], Waspaloy [20], A359 aluminum matrix [21], AZ91 magnesium [22], stainless steel P550 [23], hardened AISI D2 steel [24] and compacted graphite iron [15].

2.1. Titanium alloys

Titanium alloys are interesting materials in numerous engineering fields like engines, aerospace, vehicles, biomedical, nuclear and gas turbines etc., is predominantly due to their properties such as high yield stress, high strength to weight ratio, high toughness, high wear resistance, high creep, high corrosion resistivity, ability to retain high strength at high temperature and fine biocompatibility [25] [26]. Titanium alloys are categorized as difficult-to-machine materials because of its less elastic modulus, high chemical affinity and low thermal conductivity [26]. The life of the cutting tools is reduced when machining the Titanium alloys.

S. Sun et al. [26] performed the dry turning of Titanium alloy with different speeds, feed rates and depth of cuts and examined that the cyclic force frequency decreases inversely with feed rate and increases with cutting speed. With the increase in the cutting speed from 10 m/min to 19 m/min and 57 m/min to 75 m/min, the cutting force increases because of strain rate hardening at low and high strain rates respectively. Due to the thermal softening of the material, the cutting force declines with the increase of cutting speed outside of these cutting speed ranges. Some of the studies show that the tool life is improved by cryogenic machining than dry machining of titanium alloys. M.J. Bermingham et al. [27] investigated the effect of the cryogenic machining with different combinations of feed rates and depth of cut at constant cutting speed (125 m/min) and material removal rate ($48.5 \text{ cm}^3/\text{min}$). The combination of low cutting speed and high depth of cut enhanced the tool life 1.5 times compared to the high speed and low depth of cut combination in dry machining. Tool life in cryogenic machining is 19 min and where as in dry machining it is 12 min at the given machining conditions. Chinmaya R Dandekar et al. [13] used Laser assisted machining (LAM) and Hybrid machining to improve the tool life and material removal rate. The input parameters for the two processes are tool material and material removal temperature, the output parameters measured are cutting force, specific cutting energy, surface roughness, microstructure and tool wear. The tool life improved by a factor 1.7 using LAM for cutting speeds below 107 m/min compared with conventional machining, while tool life increased by 2 times by hybrid machining for cutting speed below 150 m/min, at a metal removal temperature of 250°C . The tool life of the K68 tool material for the same machining conditions for dry, laser assisted and hybrid machining are 28.62 min, 48.78 min and 55.10 min respectively. M.J. Bermingham et al. [28] characterized the tool life and wear mechanism for uncoated carbide tools using thermally assisted machining (TAM). This process reduces the component of cutting forces up to 30% by preheating the work piece to 350°C . The tool life is improved only up to 7%, which is insignificant compared to the over 235% improvement that occurs when coolants are used for same cutting conditions. R.A. Rahman Rashid et al. [29] studied the effect of laser beam on cutting force and cutting temperatures inspected over a range of feed rates and cutting speeds. The cutting forces are reduced by 15% over total range of cutting speeds and feed rates. The optimum feed rates for industrial application to get maximum advantage with laser power of 1200 W are between 0.15 mm/rev to 0.25 mm/rev. Below a feed of 0.15 mm/rev, there is an insignificant reduction in cutting energy, whereas above 0.25 mm/rev, the tool wear develops rapidly. While machining of titanium alloy with a laser power of 1200 W, the optimum cutting speed range is 25 m/min to 100 m/min. Above 100 m/min, the tool wear is maximum and below 25 m/min, excessive heat energy causes chip tool welding which spoils the surface integrity of the machined surface. The temperature range should be 1050°C to 1250°C to get the significant reduction in the cutting forces while machining the Titanium alloys with assistance of laser power. R.A. Rahman Rashid et al. [30] again stated that the

laser power range of 1200 W to 1600 W to be productive in reducing the cutting forces during LAM with cutting speeds between 25 m/min and 125 m/min.

2.2. Nickel based alloys

The Nickel based alloys like Inconel, Hastelloy, Nimonic, Waspaloy and Udimet, etc. have advantages over Titanium alloys made them attractive for aerospace, gas turbine and nuclear industries because of their broad range of operational temperature at extreme conditions. Nickel based alloys poses properties such as superior hot strength, hardness, very high temperature resistance, highly resistance to creep and corrosion, high thermal fatigue resistivity, high erosion resistivity, resistance to thermal shock and high melting temperature. The cutting temperatures and the forces produced while machining are very high because of high strength of the nickel alloys. Drastic increase in the cutting temperature leads to excessive tool wear and low surface quality of the machined part. In addition, the hardness of nickel alloys increases with increase in the temperature below 650 °C. Machining of Nickel based alloys are associated with low cutting speeds, bad surface finish, short tool life and high machining costs made them to call as difficult to machine materials [25].

Mark Anderson et al. [14] evaluated the machinability of the Inconel 718 under varying conditions such as feed and depth of cut by examining tool wear, cutting forces, surface roughness, and specific cutting energy. The specific cutting energy reduces by 25%, the improvement in the surface roughness is 2-3 factor and a 200-300% increase in ceramic tool life over conventional machining while the material removal temperature increases from ambient temperature to 650 °C. The surface roughness changes from 1.7 µm in conventional machining to 0.9 µm during LAM at 540 °C. The cost for machining of 1 m length of Inconel 718 decreases 50% from conventional ceramic machining and 66% from conventional carbide machining at 3 m/sec. These are the benefits of LAM. G. Germain et al. [31] presented the laser assisted machining of Inconel 718 (NiCr19FeNb at 46 HRc) with carbide and ceramic insert. LAM significantly reduces the cutting forces approximately 40% independent of cutting tool insert. The tool life of the carbide insert in LAM is less compared to conventional machining whereas the tool life of the ceramic inserts in LAM is improved up to 25% than in conventional machining. H. Attia et al. [32] studied the high speed machinability of super alloy Inconel 718 under Laser assisted and dry conditions. The tests were conducted for cutting speeds up to 500 m/min and feeds up to 0.5 mm/rev, using ceramic cutting tool (SiAlON) with Nd: YAG laser power. Under the optimum cutting conditions the surface finish improved by more than 25%, material removal rate increased by approximately 800% and there is a significant reduction in the cutting forces compared to conventional machining. Hongtao Ding et al. [20] the machinability of Waspaloy under varying conditions of metal removal temperature, cutting speed and feed is evaluated by examining tool wear, cutting forces, and surface finish. The metal removal temperature range 300 to 400 °C for machining of Waspaloy with WG-300 tools to get optimum cutting force, tool wear and surface finish. The tool life improved by 50% while machining with LAM compared to conventional machining. The decrement in cutting forces and specific cutting energy is 20% when metal removal temperature increased to 400 °C. The cutting forces for conventional machining and LAM are 205 N and 164 N respectively for the same machining conditions.

2.3. Ceramics

Advanced engineering structural ceramics such as mullite, silicon nitride, alumina, zirconia and reaction bonded silicon nitride (RBSN) have been increasingly used for production of components like valves, rotors, bearings, roller followers, cutting tools and artificial hip joints because of their properties such as high temperature strength, low density, higher wear and corrosion resistance. Due to high brittleness and hardness, machining of ceramics is very difficult. Diamond grinding is one of the machining processes to get precision parts used in industries [18] [25]. Alumina and zirconia experiences thermal fracture, while mullite and Si_3N_4 under gone plastic deformation at sufficiently high work piece temperatures, resulting in improved tool wear and surface roughness when

oxyacetylene flame used as heat source [16]. The LAM of Si_3N_4 provides significant advantages over conventional machining [27].

S. Lie et al. [18] evaluated the LAM of silicon nitride (Si_3N_4). The performance parameters like tool wear, metal removal mechanism, surface integrity and subsurface damage are measured at different input parameters such as preheating time and laser power. The tool life is improved with LAM compared to the conventional machining. The predominant mode of tool wear is adhesion which can be minimized by maintaining the cutting zone temperature which makes easy material removal. The grinding thickness is more than the thickness of layer of work piece affected by LAM (2 to 4 μm). There is no possibility of subsurface cracks on machined surface and the degradation of material strength in LAM. Patrick A. Rebro et al. [16] presented the evaluation of the laser-assisted machining (LAM) of pressureless sintered mullite ceramics. A wide range of operating conditions are set from the input parameters like laser power, beam diameter, laser tool distance, feed rate, cutting speed and depth of cut to get the optimum performance measures such as cutting forces, specific cutting energy, metal removal temperature and surface temperature. The laser power in the range 170 W to 190 W enables the decrement in the specific cutting forces, considerable amount of improvement in the tool life and work piece surface properties. To reduce the thermal cracks, the depth of cut should be approximately 0.75mm. To maintain adequate temperature gradients and avoiding thermal fracture, the feeds range from 0.012 to 0.016 mm/rev provided sufficient laser energy absorption. Thermal fracture of the work piece is due to the induced excessive temperature gradients caused by higher feed rates. Frank E. Pfefferkorn et al. [33] investigated the LAM of magnesia partially stabilized zirconia (PSZ) to determine the effect of heating on performance measures such as cutting energy, tool wear, metal removal mechanism and surface integrity using polycrystalline cubic boron nitride (PCBN) cutting tool. The specific cutting energy reduces from 6.6 to 2.6 J/mm^3 and tool life increases from 3 to 120 minutes by enhancing the material removal temperature from 530 to 1210 $^{\circ}\text{C}$. The specific cutting energy reduces with an increase in feed even though there is considerable decrement in the material removal temperature. The optimum range of material removal temperature for this matrix is approximately 900 to 1100 $^{\circ}\text{C}$. Chih- Wei Chang et al. [34] studied laser-assisted machining experiments on aluminum oxide (Al_2O_3) ceramic materials under various operating conditions like rotational speed, feed, depth of cut and laser pulsed frequency. The performance measures are surface roughness and material removal rate. Higher rotational speeds are required to get good surface roughness. The material removal temperature exceeds 850 $^{\circ}\text{C}$ means that laser power provides sufficient energy for the work piece to reach glass transition temperature and easily machined.

2.4. Ferrous alloys

Iron based hard to cut alloys are classified as low carbon ductile steels, stainless steels and hardened steels used in aerospace, automotive, chemical and food processing industries. The problem in machining of low carbon steels especially AISI 1008 is produces continuous curled chips which can scratch machined surface, jam the automatic machine tool and causes machine down. Low carbon steels tend to adhere and produce built up edge (BUE) on the cutting tool which may affect the cutting forces, tool life and surface finish of the machined part. Low thermal conductivity, high heat capacity and high strength made the stainless steels as difficult to cut materials. Hard machining is referred when the steels with hardness beyond 45HRC [25].

P. Dumitrescu et al. [24] demonstrated LAM of fully hardened AISI D2 tool steel using a high power diode laser (HPDL) in orthogonal and longitudinal turning processes. LAM removes the catastrophic fracture of the carbide cutting tools, suppresses machining chatter and saw tooth chip formation, reduces the thrust component of cutting force and increase the tool life almost 100% compared to the conventional machining. HPDL system is best suited for milling applications rather than turning because of power density limitation. S. Skvarenina et al. [15] evaluated the machinability of compacted graphite iron (CGI) whose structure yields high strength, makes it difficult to machine. By varying the feed, depth of cut and material removal temperature, cutting forces, specific cutting energy, tool wear and surface roughness are evaluated. The tool life is improved by 60% at a feed of

0.15 mm/rev, cutting speed of 1.7 m/sec (for conventional machining 19.2 min and for LAM 30.3 min) and metal removal temperature of 400 °C compared to conventional machining at a feed of 0.1 mm/rev. Surface roughness is increased by 5% as compared to conventional machining at a feed of 0.150 mm/rev. For conventional machining surface roughness is 2.35 µm and for LAM it is 2.24 µm. LAM also reduces the cost approximately 20% machining of an engine cylinder liner. Hongtao Ding et al. [35] investigated the laser assisted machining of AISI 4130 shaft by changing the operating conditions metal removal temperature, heating, cutting speed and feed rate. The cutting force and the specific cutting energy are reduced by 20% at a metal removal temperature above 200 °C compared to the conventional hard turning process. The surface roughness is in conventional machining is 1.6 µm where as in LAM it is in the range of 0.2-0.4 µm at the similar machining conditions. The hardness of the component after LAM is typically from 47 to 48.5HRC which is close to the conventional machining. LAM produces about 150 MPa more compressive surface axial residual stress than conventional machining. S.H. Masood et al. [36] present the LAM of hard to cut material, high chromium white cast iron. Laser power has a significant effect on cutting force, hardness, temperature, surface profile and cutting chips. The heat penetration increases as the distance between the laser spot and cutting tool increases, and also increases in the laser power. LAM reduces the cutting forces and feed forces to a maximum extent of 24% and 22% respectively.

2.5. Composites

Composites are usually inhomogeneous and anisotropic nature due to the presence of tough and flexible reinforcement fibres or whiskers in a brittle matrix. Surface quality issues are because of fibre pullout, delamination, uncut fibres, high dimensional deviation, and high surface roughness. The severe tool wear caused by the hard abrasive particles like SiC, Al₂O₃ etc. present in the composite are harder than the WC tools [25]. Metal matrix composites have high strength to weight ratio, high stiffness, and good damage resistance over a wide range of operating conditions, which are useful for structural applications [37]. However the composites have the good performance, their poor machinability leads to severe tool wear, less machining efficiency and difficulty in getting good surface quality [38].

Y. Wang et al. [38] presented the LAM of aluminum matrix composite (Al₂O₃ p/Al). The process parameters are cutting speed, feed rate and depth of cut, the performance measures are tool wear, cutting force and tool life. The LAM improves the tool life, reduces the tool wear and increases the wear resistance of the machined component. LAM also reduces the cutting forces to a range from 30 to 50%. Chinmaya R. Dandekar et al. [37] used the LAM for the improvement of tool life and metal removal with minimum surface damage. The performance parameters like specific cutting energy, cutting forces, subsurface damage, surface roughness and tool wear are measured by changing the material removal temperature. LAM reduces the surface roughness, specific cutting energy, tool wear, and fiber pullout compared with conventional machining. A temperature of 300 °C was set as the optimum metal removal temperature at feed of 0.02 mm/rev, a depth of cut of 0.5 mm and a speed of 30 m/min. At this condition LAM provides a 65% reduction in surface roughness, specific cutting energy, tool wear compared to conventional machining at the same cutting conditions. Also, the LAM shows an increment in the machinability of the high volume fraction, long fiber metal matrix composite (MMC) through improved material removal rate (MRR), better surface finish, increased tool life, and reduced damage. Chinmaya R. Dandekar et al. [21] studied the machining of a particle reinforced metal matrix composite (A359 aluminum matrix composite reinforced with 20% by volume fraction silicon carbide particles) using LAM. The responses such as cutting forces, specific cutting energy, surface roughness, subsurface damage and tool wear at different material removal temperature. A temperature of 300 °C was set as the optimum metal removal temperature at feed of 0.1 mm/rev, a depth of cut of 0.76 mm and a speed of 150 m/min with carbide tooling. The surface roughness and specific cutting energy is reduced by 27% and 12% respectively using LAM compared to conventional machining at the same cutting conditions. The effective tool life is improved by a factor 1.7-2.35 over conventional machining based on cutting speed when the surface roughness is 2 µm. Cutting force,

tool wear and surface roughness is reduced using LAM at all cutting speeds (50-200 m/min) than conventional machining.

3. Machining requirements

Machining advanced engineering materials in industries are usually accompanied with low productivity, high machining costs, poor surface quality and short tool life. This is because of the difficulty in dissipation of heat generated at the cutting zone, due to low thermal conductivity of these materials. The use of cutting fluids improved the machinability by reducing the cutting temperature, but improper handling of these cutting fluids can affect the environment [25]. In the process of machining, the cutting tool is subjected to high normal and shear stresses as the chips slides on the tool face leaving the work piece material [39].

4. Tools to be used

The cutting tools used in laser assisted machining should resist high mechanical and thermal stresses while machining the difficult to cut materials. The different types of cutting tools such as ceramics, cubic boron nitride (CBN), polycrystalline diamond (PCD), polycrystalline cubic boron nitride (PCBN), coated carbide inserts are used in laser assisted machining. Tool materials, at temperatures above the softening point lose their hardness. The softening point is 600 °C for high speed steel, 1100 °C for carbide, 1400 °C for Al_2O_3 , 1500 °C for diamond and cubic boron nitride tool material [40] [41]. LAM uses carbide insert for machining of aluminum oxide and mullite, PCBN for silicon nitride and zirconia [18] [33] [34] [42]. The dominant wear mechanism such as abrasion, adhesion and diffusion are observed while laser assisted machining of zirconia with PCBN [33]. Carbide inserts are used for machining of Titanium alloys for better surface roughness. For higher tool life, ceramic inserts are used for machining of nickel based super alloys, but these are not suitable for titanium alloys because of low toughness, chemical affinity and less thermal conductivity [25] [31]. LAM of composites, the carbide inserts are used to get better results in terms of improved surface integrity, material removal rate and longer tool life at higher cutting speeds [21] [37]. Carbide cutting tools are used for machining of hardened AISI D2 steel [24]. Tool wear is a major factor affecting the surface roughness of the workpiece, so if tool life could be extended, tool wear would be reduced and the workpiece surface quality relatively improved [34].

5. Lasers for machining

Light Amplification by Stimulated Emission of Radiation (Laser) is a coherent, convergent and monochromatic beam of electromagnetic radiation. A laser comprises three principal components, namely, the resonator (lasing medium), means of exciting the lasing medium into its amplifying state (lasing energy source), and optical delivery/ feedback system. The laser medium may be a solid (e.g. Nd:YAG or neodymium doped yttrium–aluminum–garnet), liquid (dye) or gas (e.g. CO_2 , He, Ne, etc.) [42].

The three major types of lasers; Carbon dioxide (CO_2), Nd:YAG and Excimer lasers are used for machining of hard-to-machine materials. CO_2 lasers are gas lasers that use gas molecules (e.g. carbon dioxide, nitrogen and helium) as the lasing medium. By increasing the vibrational energy of the molecule the excitation of the carbon dioxide is achieved [43]. CO_2 lasers have high average beam power, better efficiency and good beam quality with a wavelength of 10.6 μm in infrared region [44].

Nd:YAG lasers are solid state lasers that use dopants like Neodinium, dispersed in a crystalline matrix of Yttrium–Aluminum–Garnet ($\text{Y}_3\text{Al}_5\text{O}_{12}$) to generate laser light. Excitation in these types of lasers is attained by krypton or xenon flash lamps [45]. These lasers have shorter wavelength (1.064 μm) which can be absorbed by high reflective materials that are difficult to machine by CO_2 lasers [46].

Excimer lasers are gas lasers. The term excimer originates from ‘excited dimer’ a compound of two identical species that exist only in an excited state. Excimer complexes include argon fluoride (ArF), krypton fluoride (KrF), xenon chloride (XeCl) and xenon fluoride (XeF) with the output

wavelengths varying from 0.193 to 0.351 μm in the ultraviolet to near-ultraviolet spectra. Lasers are also characterized by the duration of laser emission - continuous wave (CW) or pulsed laser. CW lasers operate with a stable average beam power while in pulsed mode lasers generally have pulse durations of a few hundred microseconds to a few milliseconds. Pulsed lasers are more suitable than continuous wave lasers for machining ceramics as the processing parameters can be more effectively controlled [47].

6. Machining requirements

6.1. Machining setup

The setup of LAM is shown in Figure 1. The setup consists of a CNC lathe with a dynamometer, for measuring the cutting forces induced on the tool. These cutting forces are amplified using a charge amplifier. A pyrometer is used to measure the temperature of the workpiece during machining operation. Laser power is generated by a laser generator required for machining and this laser is discharged through a laser gun on to the work piece. All these are controlled by a computer controller.

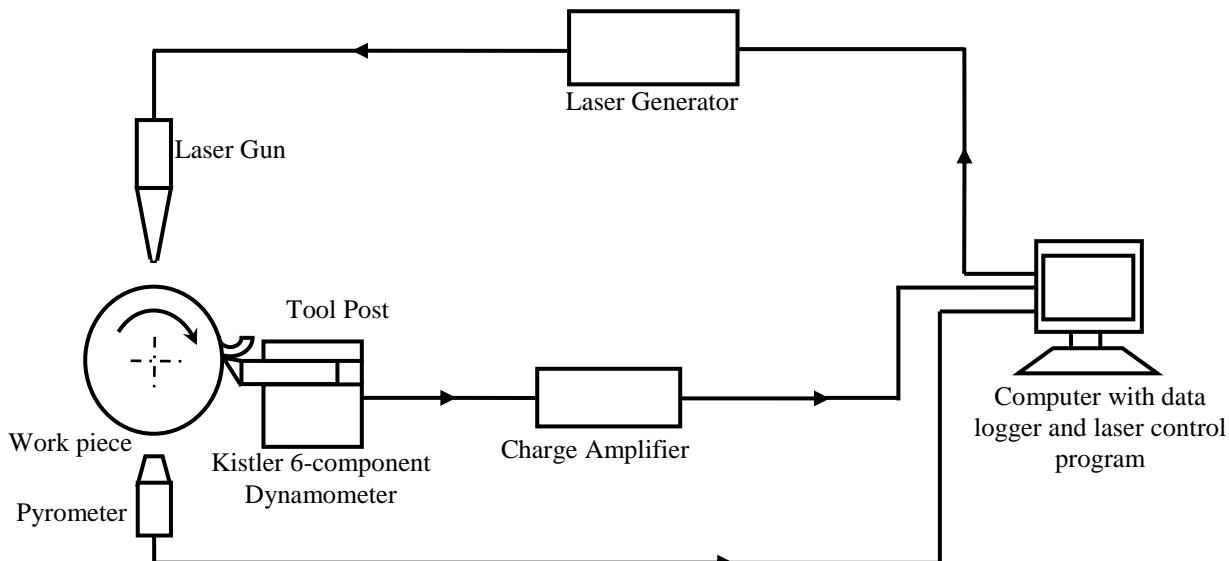


Figure 1. Schematic diagram of LAM setup

6.2. Mechanism of material removal

Laser assisted machining (LAM) is similar to the conventional turning and milling process except local heating of the work piece using laser power. Material removal mechanism is different from the conventional machining. In LAM, yield strength of the brittle material and shear strength of the ductile material is reduced to allow the plastic deformation.

Conclusion

Based on the above review, it is observed that the addition of heat during LAM process softens the surface layer of the difficult-to-cut materials so as to occur ductile deformation rather than brittle deformation during cutting. This makes the machining easy due to the reduction of cutting forces, flow stress and the friction between the tool and chip. The surface finish and other surface characteristics have been found improved with LAM.

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