Laser Assisted Machining (LAM) of Inconel 718 with Thermal Modeling and Analysis of Process Parameters

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***Abstract*— The applications of high strength materials with significant amount of heat resistant capacity is increasing in recent years in aerospace, steam turbines, automobile and nuclear science experiments. These are the materials exhibiting certain characteristics such as high temperature hardness, excessive resistance to wear at room temperature, excessive creep rupture strength etc. Laser assisted machining (LAM) is a hybrid machining process can thus improve the machinability of such materials by locally heating the material prior to removal using a conventional machining (CM) tool. The paper presented here is a study of laser assisted machining of Inconel 718(Ni Cr19 Fe Nb) having hardness (46 HRc) with ceramic insert tools. Comparing and evaluating the experimental results of conventional machining and LAM demonstrated reduction in tool wear and cutting forces and have highlighted advantages of its assistance in enhanced surface integrity.**

Keywords— LAM, Inconel 718, Superalloys , Tool life, Tool wear, Surface Integrity, Thermally supportive techniques.

I. INTRODUCTION

A Superalloy or high performance alloy is a metallic alloy that exhibits mechanical strength, elevated temperature creep resistance, surface integrity and good corrosion resistance at a temperature above 540ºC.[1,2,3]. Inconel 718 of Inconel series is a member nickel based alloy family consisting of Austenitic gamma phase and many secondary phases. Superalloys derive their strength mainly from the solid solution hardeners and its precipitated phases. Secondary phases controlling the properties of FCC carbides are MC, $M_{23}C_6$, M_6C_7, gamma prime i.e. FCC ordered Ni_3(Al Ti) and Gamma double prime i.e. BCT ordered Ni_3Nb etc.[4,2]. These materials which exhibit high resistance to wear often encounter with extreme thermal and mechanical stresses at the cutting edge during machining thus increasing the cutting forces and the tool chip interface temperature. This leads to very short tool life primarily due to chemical affinity of the tool leading to diffusion wear and strong tendency to weld to form a built up edge (BUE) of the chip.[5,6] The excessive tool-chip interface temperature during cutting operation is primarily due to poor thermal conductivity of Inconel[7,8]. The previous research conducted stated advantages of using ceramic insert tools [9], however the thermal conductivity of ceramics is very low[9] and the heat transfer rate during machining is reduced causing problems of early tool failure[9]. Due to these inherent characteristics many thermally supportive techniques have been developed enhancing tool life, machining speed etc. Laser Assisted Machining (LAM) is one of the thermally supportive technique which uses external heating source in the form of laser to soften the workpiece material surface layer so as to reduce its tensile strength and strain hardening. Comparative evaluation of the results demonstrated that the tool wear was reduced by 40%, cutting force by 18% and total MRR by 33% [10]. Thus Laser assisted machining can prove to be a effective method in machining of Inconel 718.

II. PRINCIPLE OF LASER ASSISTED MACHINING (LAM)

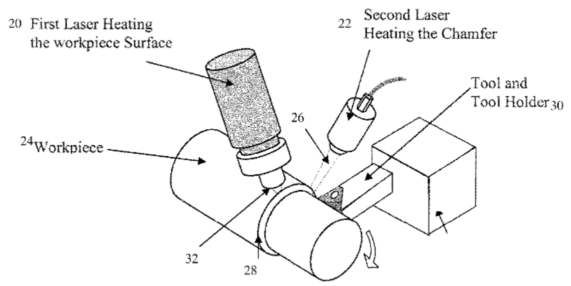

Fig 1.Schematic Diagram of LAM.

Laser assisted machining is a hybrid machining process using thermally supportive technique. In this we apply external heat source in the form of Laser to reduce the yield strength of the metal prior to material removal in the form of chip. The working of the process is based on the principle which is to reduce the cutting force necessary to machine the material by increasing the temperature to the point at which the strength of the material is reduced considerably so as to facilitate easy material removal as shown in figure 1. Hence application of this principle ensures reduced cutting energy which indeed increases the workability and machinability of the material.

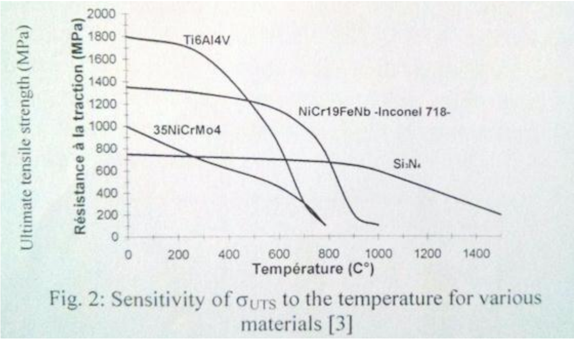

Fig 2- Characteristic behavior of Ultimate Strength.

Figure 2 shows the characteristic behavior of the ultimate strength of various materials. From the figure it can be seen that for most of the metals the tensile strength is significantly reduced at a temperature range of 500-600ºC. But Inconel retains its strength well upto 600-650ºC. Therefore in order to be effective the cutting tool must operate in the zone where the temperature should remain higher than preceding value.

III. LASER

The type of laser and its intensity plays a very important role in this process. In previous researches conducted researchers consulted the use of CO_2 laser but it may have some inherent disadvantages. The absorptivity of CO_2 laser is limited to Inconel due to which additional coating must be applied on the material so as to enhance the absorptivity. Rajagopal *et al.* [11] experimented with a 14kW CO2 laser on titanium and Inconel using coatings like silicon carbide and potassium silicate. Moreover the experimental results demonstrated the degradation of the coating due to excessive temperature and reapplication of coating during each cut in the machining cycle. This increases machining time and production cost. A recent trend is to use Nd: YAG laser of short wavelength(about 1.063 micrometer) but the major drawback faced is the high cost. Following fig shows the absorptivity of different lasers at different temperatures [12].

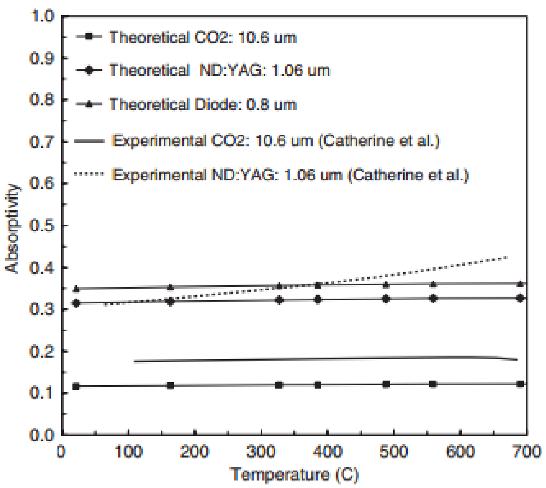

Fig. 3. Absorptivity of lasers Vs temperature.

New high powered diode lasers have come up with efficiency up to 60% far surpassing the assumed efficiency which was assumed by Tipnis et al. in 1981.The effect of angle of incidence on the absorptivity has been analyzed by Germain *et al.*[13,14]. In that research it has been particularly shown that the absorption of laser beam is almost constant for all angles of incidence less 40º relative to the normal to the surface. For all the work reported the angle of incidence was maintained at 20º. The laser nozzle can be controlled by 3 axial translations and 2 rotations. The high power laser beam is delivered through the fiber optic cable to the lathe chamber and focused on the workpiece. During the machining process a 2’’ flat high pressure air nozzle delivering 125 Psi pressure is placed in order to protect the focusing lens from damage by the chips formed [15].

IV. THERMAL MODEL.

Mathematical modeling and simulation is used to study and gain insight the parameters and mechanisms which take place during heating of the rotating workpiece and a moving laser source.

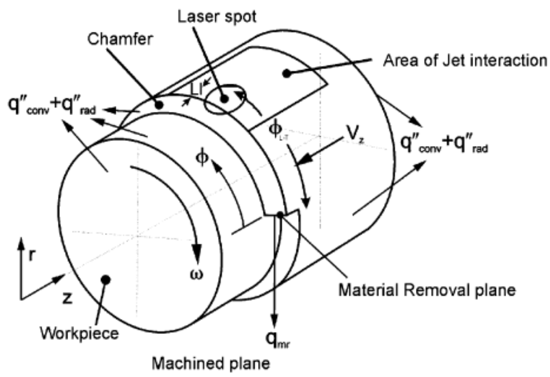

Fig 4.Thermal Model of LAM by Rozzi et al.

This model is based on the model which developed by Rozzi *et al.* [16,17]. The schematic diagram is shown in the figure 4 . The laser heat source is assumed to have Gaussian heat source. It is having maximum heat flux at its center of the beam. The diameter of the laser spot is governed by the equation $D_{laser}=0.241d_d+0.170$ …………(1)

Where,

D_{laser} – Diameter of the laser on the workpiece.

d_d- Distance from the focal point of the system.

The heat flux distribution over the surface is given by the equation 2. [18,19]

Assuming isothermal conductivity and neglecting the heat generated during the oxidation of the metal. So the equation governing the conduction in the rotating workpiece going under the moving heat source is given by equation 2. [18,19]

$$\underbrace{\rho\omega\frac{\partial h}{\partial\phi}+\rho V_z\frac{\partial h}{\partial z}}_{\text{advection}}+\underbrace{\rho\frac{\partial h}{\partial t}}_{\text{storage}} = \underbrace{\frac{1}{r}\frac{\partial}{\partial z}\left[rk\frac{\partial T}{\partial r}\right]+\frac{1}{r^2}\frac{\partial}{\partial\phi}\left[k\frac{\partial T}{\partial\phi}\right]+\frac{\partial}{\partial z}\left[k\frac{\partial T}{\partial z}\right]}_{\text{conduction}}+\underbrace{q'''}_{\text{generation}},$$

…….(2)

where r is the density in kg/m3, o the rotational speed in rad/s, h the enthalpy in J/kg, k the thermal conductivity in W/mK, and r, f, and z are cylindrical coordinates in m.

V. ANALYSIS

A. EFFECT OF CUTTING SPEED ON CUTTING FORCES.

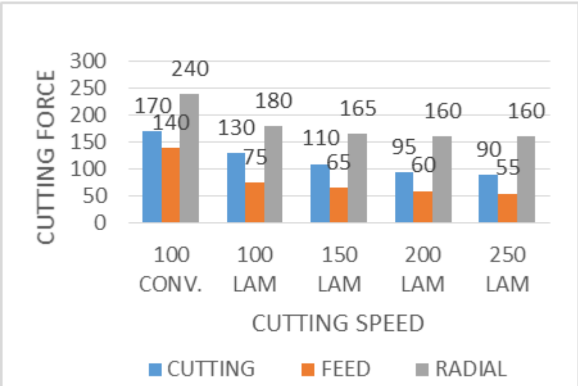

Fig 5. Graph of Cutting Forces vs Cutting Speed.

Figure 5 shows the 3 forces (N) under conventional and LAM condition using a triple layer coated carbide tool (KC8050). A 3000W LAM at feed 0.25mm/rev with depth of cut (DOC) is equal to 0.25 is demonstrated. Aberrant declivity is observed in 3 forces as the laser is in effect. Force reduction upto 25% is observed. The laser power limit the stability of the strengthening precipitates of Inconel 718 at 650ºC [15] resulting into sharp reduction in materials yield strength. The trend of reduction in forces limits at around 200m/min as a result of poor absorptivity laser power at high cutting speed. This is evident from fact that there is stability in surface temperature. Hence optimum cutting parameters with 200m/min cutting speed is most suitable for machining.

B. EFFECT OF CUTTING FORCES ON TOOL WEAR

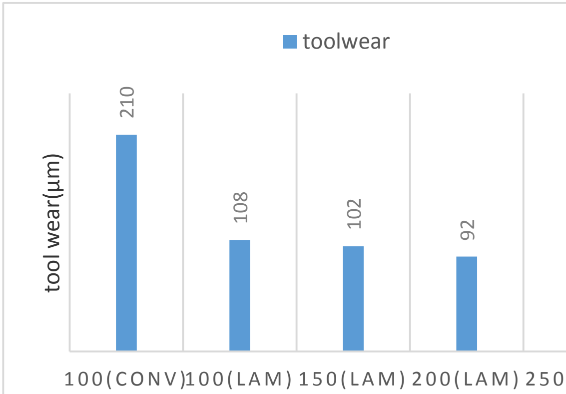

Fig 6.Graph of Tool Wear vs Cutting Speed.

From the graph it is evident that there is a sharp reduction in the flank wear of the tool from 210µm to 108µm when laser is in action. The reason primarily being nickel alloys demonstrate negative partition temperature resulting into reduced heat removal from the tool chip interface. This causes stress concentration to occur on the maximum heated zone thus resulting into rapid tool wear. But once the laser is in use a more favourable heat gradient is created a hence more favourable temperature distribution is achieved resulting into reduced flank and rake wear. The existence of hard abrasive phases cater to increased wear but in case of laser assisted machining the hard phases are soften due to elevated temperature and further reduce the tool wear rate. Increase in tool wear is observed after 200(LAM) because of the reduced absorptivity of laser with increase in speed due to lack of available time for heating the cutting zone. Hence speed of 200m/min is recommended for optimum cutting results [15].

C. EFFECT OF CUTTING SPEED ON SURFACE ROUGHNESS.

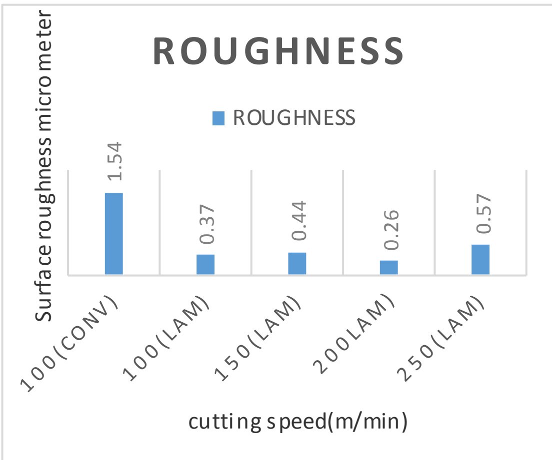

Fig 7. Graph of Surface Roughness vs Cutting Speed.

Surface roughness is a major issue in machining of Inconel. Metal tearing and smearing are the primary causes of the degraded surface finish. However laser tends to improve the surface finish due to reduced tool wear and material strength. The increase in surface roughness is observed above 250 (LAM) is because of the increased tool wear due decrease in laser absorptivity and thus failing to reduce the material strength [15].

D. EFFECT OF FEED ON CUTTING FORCES.

During the experiment the cutting speed was kept at 200m/min. From the graph it is evident that there is a steady increase in the cutting forces with the increase in the speed. Increased feed above 0.25mm/rev is because of the reduced heating effect of laser due to decrease in absorptivity of laser. Moreover with increase in feed thicker chip is generated hence increased forced on the tool. Hence the forces rapidly increase with the increase in the feed. The maximum allowable forces depend upon the tool strength [15].

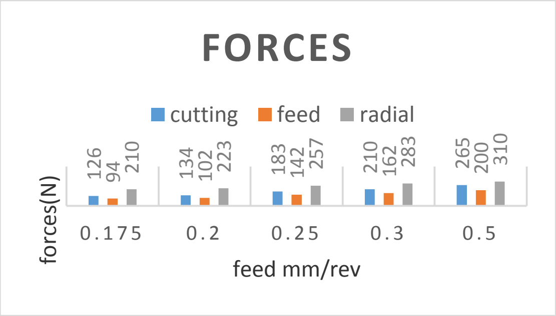

Fig 8.Graph of Cutting Forces vs Feed.

E. EFFECT OF FEED ON TOOL WEAR.

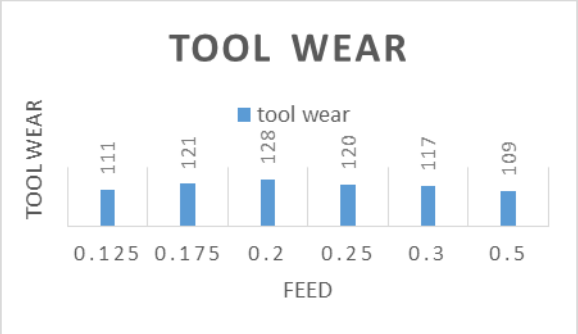

Fig 9.Graph of Tool Wear vs Feed.

As illustrated above the tool wear increases till 0.2mm/rev and again reduces with the increase in feed. During the initial feed the chip thickness being very small results into uneven pressure distribution thus results into tool wear. As the feed increases the uniform pressure distribution leads to enhanced tool life by reducing the tool wear [15].

F. EFFECT OF FEED ON SURFACE ROUGHNESS

As per the figure 10. the surface roughness decreases with the increase in feed due to the thermal softening upto 0.25mm/rev but with increase in feed the power absorption capacity is limited. Hence the forces on the tool is increased along with the increased tool wear and hence leads to increased surface roughness [15].

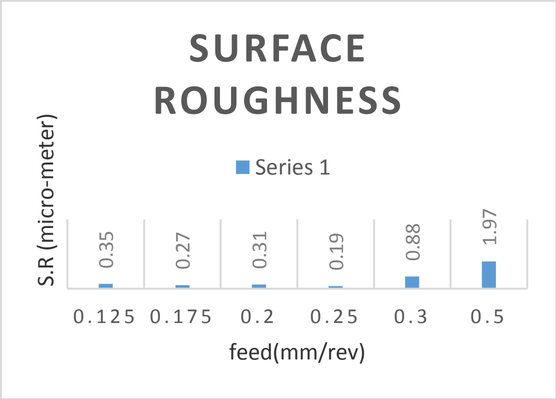

Fig 10.Graph of Surface Roughness vs Feed.

VI. CONCLUSION.

- With the help of laser assisted machining the machinability of hard to wear materials is reduced significantly.
- With the application of laser it is important to optimize the spot size and laser intensity for optimum machining conditions.
- Choosing the optimum parameters while machining the MRR along with the tool life can be increased significantly.
- The processes can be further improved by using high temperature lubricants while machining using tribological approaches. MoS_2 powder infused on the metal surface using micro arc oxidation process (MAO) can further improve the surface roughness.
- Use of LAM will decrease machining cost and machining time by reducing the number of machining passes and thus overall increase the machinability.

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