Chapter 3

Experimental Details

3.1 INTRODUCTION

This chapter discusses the detailed description for the laser assisted hybrid machining facility and its subsystems such as laser source, laser head and fixture. The detailed procedure for selection of measuring instruments, specifications and measuring methods are explained. Furthermore, the experimental procedure, selection of process parameters and experimental plan is discussed.

3.2 LASER ASSISTED HYBRID MACHINING (LAHM) FACILITY

The laser assisted hybrid machining system consists of a Nd:YAG continuous wave laser source with a maximum power of 2 kW and high speed lathe with maximum spindle speed of 3600 rpm. A cooling tower is placed behind the Nd:YAG laser source such that the laser system is continuously water cooled using a chiller unit. In the integration process, the laser beam is directed to the workpiece and creates a thermal softening to the workpiece prior to machining. An optical fiber cable connects the output of the laser source to the laser head. The output of the laser head is collimated with a circular spot size of 2 mm diameter laser beam. The laser head is mounted on a specially designed fixture and coordinated with the tool holder in feed direction for axial movement. The main benefits of fixture is that it can accommodate laser delivery head with focal length from 120 to 250 mm and the angular position of laser beam delivery that can be varied between 60 to 90°.

A compressed air jet is supplied to the laser head using a sharp edged rectangular orifice to protect the focusing optics from any debris generated during machining. The positioned laser head on the fixture delivers the laser beam in such a way that the laser beam center always strikes the centerline of the cylindrical work piece during scanning. The laser beam strikes the workpiece on the rotating spindle that is set at a desired speed. The surface temperature of the workpiece is recorded continuously using a dual wavelength infrared pyrometer. The cutting force components are measured using a Kistler dynamometer which is attached on the tool post. The major element of the laser
assisted hybrid machining setup is shown in Figure 3.1. The schematic view of laser assisted hybrid machining system is shown in Figure 3.2.
3.3 DESCRIPTION OF SUBSYSTEMS IN LAHM

3.3.1 LASER SOURCE

The three components for laser configuration system are: (1) the laser Nd:YAG system, (2) the laser head and (3) special purpose fixture design. In the present work, Nd:YAG continuous wave laser (model: JK2003SM) has been used. The advantages of Nd:YAG laser are low initial cost and medium operating cost. The Nd:YAG laser shows an absorption rate of about 25-35% for metal surface. It is a class IV laser system that produce a single wavelength (1064 ± 10 nm), laser beam at power levels up to 2 kW without modulated. The detailed specification of the Nd:YAG laser source is listed in Table 3.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Average laser Power (W)</td>
<td>2000W</td>
</tr>
<tr>
<td>Max. Modulated Peak laser Power (W)</td>
<td>4000W</td>
</tr>
<tr>
<td>Beam Quality ½ Angle-Radian (mm.mrad)</td>
<td>24</td>
</tr>
<tr>
<td>Optical fiber diameter (µm)</td>
<td>600</td>
</tr>
<tr>
<td>Modulated Frequency (Hz)</td>
<td>100-1000</td>
</tr>
<tr>
<td>Output Mode</td>
<td>CW, Sine or Square</td>
</tr>
</tbody>
</table>

3.3.2 LASER HEAD

The laser output from the source is delivered to a right angled laser focusing head through a fibre optic cable of 15 m long. The laser focusing head consists of a base focus head with collimating lens and a focus lens module. The modular construction of the delivery head allows the user to configure the optimum spot size to meet production needs. Construction is as follows: The laser beam from the optical fiber cable is collimated. Then, the collimated beam can be magnified or de-magnified by choosing appropriate focusing optics lens to obtain optimum laser spot radius. To ensure optimum beam heat intensity at high power and proficient operation of the optics, operating temperature of the laser head is equipped with a compressed air that cools the collimating and focusing optics to keep the process conditions more homogenous. A chiller is used to continuously cool the beam flow components in the Nd:YAG laser system. The photograph of laser focusing head and fibre optic cable is shown in Figure 3.3.
3.3.3 FIXTURE FOR HOLDING LASER DELIVERY HEAD

In order to hold the laser delivery head properly during machining a special fixture is required. The fixture should move along with the tool carriage without any distortion to maintain the laser spot at the required position on the work material. The product specification: overall weight=5 kg, overall size= 85 x 250 x 450 mm, defocusing lens axis adjustment distance= 0-50 mm, approach angle= 0-60° normal to the tool, adjustment movement in x-axis, parallel to tool =0-5 mm. In the current work, a provision is given in the fixture for varying the laser beam position (approach angle). The solid model of the fixture design for the present LAHM setup is shown in Figure 3.4.

Figure 3.3 Photograph of laser delivery head

Figure 3.4 Fixture for holding laser delivery head (a) CAD model (b) Physical model
3.4 DESCRIPTION OF MEASURING EQUIPMENT IN LAHM

3.4.1 TEMPERATURE MEASUREMENT USING INFRARED PYROMETER

Irrespective of the type of the laser source used, a key success of LAHM 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. In the present study an infrared dual wavelength pyrometer manufactured by Williamson Inc., Model Pro 91-25C-FOV350 mm with a range of 500-2000°C is used. The photograph of the infrared pyrometer used in this work is shown in Figure 3.5. The pyrometer is mounted at location provided in the fixture and moves along with the laser beam and cutting tool in the axial direction. Thereby, the surface temperature is measured at a fixed distance from the cutting zone and the laser impingement location. The compressed air at a pressure of 4 bar is focused between pyrometer and the workpiece using a sharp-edged rectangular orifice.

![Figure 3.5 Photograph of infrared pyrometer](image)

3.4.2 FORCE MEASUREMENT USING DYNAMOMETER

Three-component piezoelectric Kistler dynamometer (Model 9257B) is used for force measurements. The output from this piezoelectric dynamometer is carried by a connecting cable to the multichannel charge amplifiers. Then, it is connected to analogue to digital converter and the data acquisition system. The cutting tool is mounted on the force dynamometer using a tool holding fixture. The photograph of dynamometer and the amplifier is shown in Figure 3.6. The experimental data are collected at the
maximum 1 kHz acquisition rate, and each set of 250 data points is averaged, resulting in the acquisition of an average cutting force every 0.5 seconds.

Figure 3.6 Kistler dynamometer for force measurement

3.4.3 SURFACE ROUGHNESS MEASUREMENT

Surface roughness measurement along the work piece axis are done using surface profilometer (Marsurf GD120) [Make: Marwin, Germany]. The specification of the equipment used for measuring surface roughness is given below: Standard : JIS 94, Cut-off : 0.8 mm, Filter : Gauss type, Sampling length : 0.8 mm, Assessment length : 4.00 mm, Levelling : ALL, Assessing speed : 0.5 mm/s.

Figure 3.7 Photograph of surface profiler
The set-up used for the measurement of surface roughness is shown in Figure 3.7. After completion of each machining experiment the roughness was measured on the machined surface parallel to the axis. For each trial, three measurements are taken on the surface and the average value is considered for the analysis.

3.4.4 TOOL WEAR

The tool wear of cutting insert was measured using a VISIO 300 DCC optical image analyser. The microscope has been calibrated against standard block gauges. The measurements are done using digital camera imagery acquired by computer software. The optical measuring microscope used in the present study is shown in Figure 3.8. For quantifying the tool wear, an average flank was chosen as the index. After every predetermined interval, the flank wear on the insert was measured using the optical image analyser.

![VISIO 300 DCC video measuring system](image)

**Figure 3.8 Photograph of VISIO 300 DCC video measuring system**

3.4.5 MICROSCOPIC ANALYSIS OF SUBSURFACE DAMAGE

Subsurface microstructural analysis was carried out using optical microscope. The etchant is a Keller’s solution (5 ml hydrochloric acid, 3 ml acetic acid, 3 ml of nitric acid and 2-3 drops of glycerol). The equipment used for this examination is Zeiss Optical microscope shown in Figure 3.9. Zeiss optical microscope is capable of capturing images from 100X to 1000X of magnification.
For subsurface microstructure analysis, a small cubical sections (10 mm x 5 mm x 8 mm) of the laser scanned workpiece are cut from cylinder bar using wire electro-discharge machining. The cut samples are hot mounted in Bakelite and prepared metallographically in order to achieve a mirror like surface. Subsurface microstructural analysis are conducted with a maximum of 200 × magnification. The depth of microstructural deformation measurements are conducted by taking a number of measurements at random positions across each cut section.

3.4.6 MEASUREMENT OF MICROHARDNESS

The equipment used to measure the microhardness is shown in Figure 3.10. Microhardness testing is performed using Vickers microhardness across the heat treated track to study the variation of hardness due to the change in the microstructure. The hardness measurement was carried out with a load of 500 gram and a dwell time of 15 sec as per AST M E384. The diamond with an apical angle of 136° was used for indentation. The two diagonals of the indentation left in the surface of the material after removal of the load were measured using a microscope and their average value is used for Vickers Pyramid Number (HV) calculation. The measurement of microhardness was performed into the depth of material along a straight line perpendicular to the machined surface. The first point of microhardness measurement was located at a distance of up to 15 μm from
the machined surface, depending on the profile hump or caving. The second measurement was performed at the depth of 20 μm; the successive ones were performed at 20 μm intervals until the hardness of bulk material was obtained. The bulk microhardness was measured at 3.2 mm below the machined surface.

![Figure 3.10 Vicker’s hardness test equipment](image)

3.4.7 CHIP MORPHOLOGY STUDY

The measurement of the geometrical parameters of chip formed during LAHM of Inconel 718 has been made to investigate the chip morphology. A microscopic observation of chip has been carried out for all the cutting conditions. Chip for various cutting conditions are collected during each machining trials. In order to mounting, the chip is cut with small length of 5 mm is placed in wax with sandwich like fashion and positioned in such a way that the longitudinal cross-section of the chips is facing upwards i.e. the surface which is to be ground and polished. The polishing of the chip samples are performed using a silicon carbide paper of 220 grit size followed by disc polishing machine. The samples are analyzed under an optical microscope. Chip thickness is measured at three separate locations using the microscope.
3.5 EXPERIMENTAL PROCEDURE

3.5.1 MATERIAL CHOSEN FOR THE PRESENT STUDY

The cylindrical work piece of Inconel 718 super alloy with 25 mm diameter and 300 mm length supplied by Bharath aerospace alloys, Mumbai is used in the present study. The average hardness of the material is measured as 48 HRC. The material is solution heat treated and aged as per AMS 5663M. No coating has been applied to the work piece surface to improve the absorptivity. The optical microstructure of Inconel 718 alloy as received sample is shown in Figure 3.12. It is observed that grains are uniformly distributed. Microstructure of Inconel 718 consists of austenite FCC matrix known as gamma (γ) and can be strengthened by solid solution strengthening (Fe, Mo, Cr) in nickel together with other secondary phases and precipitation hardening (Ti, Nb, Al) by forming intermetallic phases. The chemical composition and mechanical properties of Inconel 718 are listed in Table 3.2.

![50 μm](image)

**Figure 3.11 Microstructure of the Inconel 718 alloy for received condition**

| Table 3.2 Chemical composition and mechanical properties of Inconel 718 |
|------------------|---|---|---|---|---|---|---|---|---|---|
| Elements         | C  | Mn | Si  | Ti | Al | Co | Mb | Cb | Fe | Cr | Ni  |
| Percentage       | 0.08 | 0.35 | 0.35 | 0.6 | 0.8 | 1.0 | 3.0 | 5.0 | 17.0 | 19.0 | 52.82 |
| Mechanical Properties | Density (g/cm³) | Melting Point (°C) | Specific heat (J/kg/k) | Thermal conductivity (W/mK) | Yield strength (MPa) | Tensile strength (MPa) |
|                  | 8280 | 1260-1350 | 425 | 11.4 | 1260 | 1430 |
3.5.2 SELECTION OF CUTTING TOOL

The cutting tool used for the laser assisted hybrid machining experiments is PVD coated (TiAlN) carbide inserts. TiAlN has significantly higher hot hardness of above 750°C. At 1000°C, TiAlN is considerably harder than TiCN and TiN. The higher hot hardness of TiAlN coatings is due to the solid solution effect of either carbon or aluminum in the TiN lattice. It also exhibits good high temperature chemical stability and has high resistance to abrasive wear. It is a result of the propensity of TiAlN coating to form a protective outermost layer of Al₂O₃ and an intermediate layer comprising titanium, aluminium, oxygen and nitrogen during the machining operation, leading to higher oxidation resistance. Finally, TiAlN has the lowest thermal conductivity and result in lower tool tip temperature. The specification of cutting insert and tool holder is CNMG 1204 08-MS-KC5525 and PCLNR 2020 K12 respectively. The tool signature of the carbide cutting insert is given in Table 3.3.

<table>
<thead>
<tr>
<th>Tool signature of PVD coated carbide Insert</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back rake angle</td>
</tr>
<tr>
<td>–6°</td>
</tr>
</tbody>
</table>

3.5.3 SELECTION OF PROCESS PARAMETERS

In laser assisted machining, the control factors that affect process efficiency are of two different sets. The first is machining parameters namely cutting speed, feed rate, depth of cut and tool type. The second one is the factors associated with laser assistance namely laser power, laser spot size, position of laser beam to the cutting tool. Based on the review of literature, laser power, approach angle of laser beam, cutting speed and feed rate are considered to analyse the effect on process performance. A constant axial distance of 2 mm between the laser spot to cutting tool and spot size of 2 mm diameter is maintained due to the low heat conductivity of the Inconel 718 alloy and further to avoid excessive heating which affects the cutting tool (Graci et al., 2013).
3.6 EXPERIMENTAL PLAN

The experiments are planned according to design of experiments (DOE) approach. In phase I, the experiments are performed based on $L_{31}$ array of experimental design using face-cantered central composite design (CCD) in response surface methodology. In this phase, cutting speed, feed rate, approach angle and laser power are varied each at three levels. In phase II, laser assisted machining experiments are performed based on full factorial experimental design approach with two replications. In this phase, cutting speed, feed rate and laser power are varied each at three levels to analyse the machinability characteristics. Here the factor levels are decided based on the results obtained from phase I. Laser beam approach angle is kept at the constant value of 60°. The machining performance of LAHM process is assessed by measuring the responses such as cutting force components, surface roughness, flank wear, cutting temperature, microhardness and chip geometry. In phase III, tool life and surface integrity analysis are carried out for long run test.

3.7 SUMMARY

This chapter discussed the integration of laser source with high speed machining lathe. Description for Nd:YAG laser system, the experimental setup, laser head and special purpose fixture has been discussed. The description for measuring instruments for the various components such as temperature, cutting force, surface roughness, tool wear, microstructure characterization, microhardness and chip characteristics is discussed. The chemical composition and mechanical properties of Inconel 718, cutting tool details, selection of process parameters are also discussed.