Expert System Approach for Manufacturability Evaluation of Nd: YAG Laser Beam Machining Process

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Received: 19 January 2017, Revised: 4 February 2017, Accepted: 5 March 2017

Abstract: In this paper, an expert system (ES) is developed for manufacturability evaluation of ND:YAG laser in computer based concurrent engineering. The expert system evaluates machining cycle time and cost in less than 30 seconds. Experimental verification and validity of the expert system is carried out**.** The results of expert system are compared with the results of experimental laser beam machine**.** Results are presented. The results of the expert system show machining cycle time and cost for expert system is about 10 percent less than the experimental one. In addition material is selected by the expert system. It gives valuable information to help designers and manufacturing engineers to improve design and manufacturing. The expert system links with design feature library, material database and laser beam machine database. The design specification is acquired through a feature based approach. Material database holds attributes of more than 10 types of materials. Laser beam machine database holds attributes of 2 types of laser beam machine and machine parameters. For each design feature, the expert system provides information needed for manufacturability evaluation and estimation of machining cycle time and cost. It can be used for design and manufacturing optimization. The expert system can be used as an advisory system for designers and manufacturing engineers. It can be used as a teaching program for new laser operators in computer based concurrent engineering environment**.**

Keywords: Design, Expert system, Manufacturing, ND: YAG Laser

Reference: Sadegh Amalnik, M., "Expert System Approach for Manufacturability Evaluation of Nd:YAG Laser Beam Machining Process", Int J of Advanced Design and Manufacturing Technology, Vol. 10/ No. 2, 2017, pp. 15–24.

Biographical notes: Morteza Sadegh Amalnik received his PhD in Mechanical Engineering from University of Paisley 1996. He is currently Assistant Professor at the Department of Mechanical Engineering, Qom University, Qom, Iran. His current research interest includes conventional machining, non-traditional machining, Computer integrated manufacturing, artificial intelligent system, design for manufacturing, Rapid prototyping and Rapid Tooling technology development.

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1 INTRODUCTION

Planck in 1900 has defined the concept of quanta and in 1920 it was well accepted that apart from wavelike characteristics of light it also shows particle nature while interacting with matters and exchange energy in the form of photons. The initial foundation of laser theory was laid by Einstein who has given the concept of stimulated emission.

Various kinds of laser are used in industries. Among various kind of lasers, CO_2 and Nd: YAG are the most kind used in industries [3]. Nd: YAG lasers have low beam power but when operating in pulsed mode high peak powers enable it to machine even thicker materials. Also, shorter pulse duration suits for machining of thinner materials [4]. In laser beam when a high energy density is focused on small area of work surface, the thermal energy is absorbed which heats and transforms the work volume into a molten, vaporized or chemically changed state that can easily be removed by flow of high pressure assist gas jet [5]. The key elements of LASER beam process are thermal properties and, the optical properties rather than the mechanical properties of the material to be machined. The energy transfer between the laser and the material occurs through irradiation. When a laser combined with a multi-axis workpiece positioning system or robot, the laser beam becomes flexible and can be used for drilling, cutting, grooving, welding and heat treating processes on a single machine, milling [6].

The researchers have described importance aspect of laser and proposed different mechanisms of material removal during laser machining. Laser milling of ceramics [7] have been proposed by fracture technique in which a focused laser beam is used to scribe the grooves on the work surface, and then a defocused laser beam is used for heating this zone. The heat induces the tensile stress and the stress concentration increases at the groove tip which results the fracture in the direction of groove cracks. Researchers [8] have studied the application of laser milling for rapid manufacturing of micro-parts of difficult to machine materials by using layer by layer material removal technique through chemical degradation. Other researchers [9] have studied the laser milling of alumina ceramic and found that the milling quality was superior for laser milling in water but the efficiency was reduced as compared with laser milling in air. Combination of LBM with other machining processes, have been attracted. Usually, the performance of hybrid machining process is better than the sum of their performance with the same parameter settings [10]. In laser assisted turning, the laser heat is focused on the un-machined section of the part directly. The addition of heat softens the surface layer of difficult-to-turn materials, so that ductile deformation takes place rather than brittle deformation during cutting. This process yields higher MRRs while maintaining part surface quality and reduces cost of machining [11]. Researchers [12] have defined Laser as a light amplification by stimulated emission of radiation, a coherent and amplified beam of electromagnetic radiation. Laser beam machining (LBM) is a thermal energy based machining process in which the material is removed by 1) melting, 2) vaporization, and 3) chemical degradation (chemical bonds are broken which causes the materials to degrade). When a high energy density laser beam is focused on small area of work piece the thermal energy is absorbed which heats causes the work volume into a molten, vaporized or chemically changed state that can be removed workpiece by flow of high pressure assist gas jet. Nd: YAG laser beam machining (LBM) process has a great potential to manufacture complex shaped products. In practical applications, such as drilling, cutting, or scribing, the optimal combination of Nd: YAG LBM process parameters needs to be selected to provide the desired machining performance. Laser light differs from ordinary light because it has the photons of same frequency, wavelength and phase. Laser light is high directional, have high power density and better focusing characteristics. Increasing demand for advanced materials and availability of high-power lasers have stimulated interest among the researchers for the development of laser machine [1]. LASER technology is a high flexibility and productivity, noncontact processing, elimination of finishing operations, adaptability to automation, reduced processing cost, improved product quality, greater material utilization, processing of materials irrespective of electrical conductivity, minimum heat affected zone (HAZ), and green manufacturing. Among various types of lasers used in industries, CO_2 and Nd: YAG lasers are the most used. Nd: YAG LBM is a complex dynamic machining process with numerous parameters, like lamp current, air pressure, pulse width, pulse frequency, and cutting speed, so in order to maintain a high production rate and acceptable quality for cutting and machined parts, it is important to select the optimal parameters, because these parameters directly affect on the physical characteristics of the part, such as surface roughness, kerf width, HAZ thickness and taper. This process also does not involve any mechanical cutting force and tool wear.

Recently LBM are used for several material processing operations, such as laser micro drilling, cutting, micro grooving, micro turning and marking [2]. The laser is also used to perform turning, milling operations. The important factor in laser is the light amplification achieved found that the laser-assisted turning (LAT) of silicon nitride ceramics economically reduces the surface roughness and tool wear in comparison to only conventional turning process. Laser assisted turning of alumina ceramic composite (Al_2O_3p/Al) has reduced the

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cutting force and tool wear by 30–50% and 20–30%, respectively, along with the improved surface quality as compared with conventional turning [13]. Investigators have also found a reduction of 20–22% in cutting force with a better surface quality during laser-assisted planning of alumina ceramics [14]. The thrust force in laser-assisted micro-grooving of steel has been found to be reduced by 17% as compared with conventional micro-grooving processes [15]. Researchers found that both the aspect ratio (depth over diameter) and the wall surface finish of the micro-holes were improved by using the ultrasonic vibration-assisted laser drilling, compared to laser drilling without assistance of ultrasonic vibration [16]. Holes with much smaller recast layer during ultrasonic-assisted laser drilling as compared with the laser drilling without ultrasonic aid [17].

Laser-assisted seeding (a hybrid process of LBM and electro-less plating) process have proven to be superior than conventional electro-less plating during plating of blind micro-vias (micro-vertical interactions) of high aspect ratios in printed circuit boards (PCBs) [18]. Kuar et al., [19] performed RSM-based parametric analysis to investigate the change in the responses with the input parameters, such as pulse frequency, pulse width, lamp current, and assist air pressure, for achieving minimum height of the recast layer and maximum depth of the microgroove. Parametric optimization of the kerf quality characteristics (kerf width, kerf taper, and kerf deviation) have been performed by researchers during pulsed Nd: YAG laser cutting of nickel-based super alloy thin sheet [20].

The effects of different process parameters on hole circularity at exit and taper of the hole during Nd: YAG laser micro-drilling on gamma-titanium aluminide have been investigated [21]. Kibria et al., performed experimental analysis on Nd: YAG laser micro-turning of cylindrical-shaped ceramic materials to achieve the desired responses, that is, depth of cut and surface roughness while varying the laser micro-turning process parameters, such as lamp current, pulse frequency, and laser beam scanning speed [22].

Researchers observed the effects of five parameters on circularity and taper of holes in pulsed Nd: YAG laser micro-drilling process and concluded that the circularity of the drilled hole at entry, exit, and taper were the important attributes influencing the quality of the hole [23]. Biswas et al. investigated the effects of lamp current, pulse frequency, pulse width, air pressure, and focal length of Nd: YAG laser micro-drilling process on hole circularity at entry and exit using RSM-based experimental results [24]. Investigators applied grey relational approach for determining the optimal process parameters to minimize HAZ and hole circularity and maximize MRR in pulsed Nd: YAG laser micro-drilling on high carbon steel [25]. Researchers presented a hybrid design strategy for determining the optimal laser drilling parameters in order to simultaneously meet all the requirements for seven quality characteristics of the holes produced during pulsed Nd: YAG laser drilling on a thin sheet of nickel-based super alloy [26]. Artificial bee colony algorithm is an evolutionary computational technique, developed in references [27-28].

2 PROCESS PARAMETERS AND PERFORMANCE

For development of expert system, knowledge of process parameters is very important. Experimental studies on LBM by researchers show the effect of process input parameters on process quality, process performance, surface finish and material removal rate and heat effected zone (HAZ) [29-51]. Process input parameters include:

- Laser power,
- Type of assist gas
- Pressure of assist gas,
- Cutting material thickness
- Type of Material:
- Cutting speed and
- Type of operation mode (continuous or pulsed mode)

Process performance: experimental studies about parameters affect on process performance of LBM show that the following parameters are very important [29-51]:

- Material removal rate(MRR)
- Laser power,
- Type of assist gas
- Pressure of assist gas,
- Cutting material thickness
- Machined geometry (kerf width, hole diameter, taper)
- Material composition,
- Cutting speed
- Type of mode of operation (continuous wave (CW) or pulsed mode.

The important parameters influencing on MRR in laser beam machining are the following factors [29]-[35]:

- MRR first increases and then decreases after a critical value with increasing power density for all metals tested. [29].
- MRR and Cutting speed of continuous wave (CW) is more than pulsed Nd:YAG laser beam[30].
- MRR and cutting speed depend on pulsed mode, pulse frequency and peak power [31].

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- Low pulse frequencies and high peak powers effect on MRR and cutting speeds [32].
- MRR depends on machining speed and/or machining Cutting speed, peak power and cutting velocity [33].
- Higher cutting speeds depends on low pulse frequencies and high peak powers
- Compressed air removes more material in comparison to argon inert gas during laser cutting [34].
- The effect of pulse intensity on depth of cut or MRR during pulsed Nd: YAG laser cutting [35]

The quality of machining depends on the following parameters [30-51]:

- The quality of machining are cut width/ hole diameter and taper formation.
- Kerf width or hole diameter reduces the taper.
- Oxygen or air gives wider kerf while use of inert gas gives the smallest kerf.
- Increasing frequency causes the kerf width decreases.
- Material type and its thickness effects on hole taper during Nd: YAG laser
- Taper angle decreases with increasing pulse frequency
- Pulse energy has no significant effects on hole taper.

Parameters effects on surface roughness are the following factors [43-47]:

- Nitrogen gas gives better surface finish than oxygen
- surface finish is better at higher speeds
- Surface roughness depends on laser power and cutting speed [44].
- laser power, cutting speed and frequency have a major effect on surface roughness [45]
- surface roughness value reduces on increasing pressure
- Laser gives better surface finish in water as compared to air [46].
- air pressure gives poor surface roughness
- surface roughness reduces on increasing cutting speed and frequency,
- surface roughness decreases the laser power and gas pressure
- surface roughness reduces by using nitrogen assist gas and lesser power intensities
- Surface roughness depends on middle range of operating parameters such as pulse frequency, lamp current and cutting speed [47].
- surface roughness depends on laser power and cutting speed [48]

Parameters effects on heat affected zone are the following factors [49-51]:

- Controlling various factors of LBM can minimize the heat effected zone (HAZ)
- Low material thickness and pulse energy gives smaller HAZ [40].
- Decreasing power and increasing feed rate generally led to a decrease in HAZ [49].
- Low material thickness and pulse energy gives smaller HAZ [50].
- Pulsed laser cutting using low wavelength laser with low pulse width gives less HAZ
- Increasing the beam angle to surface nickel decreases the HAZ [51].
- Medium pulse energy, may obtain minimum HAZ

3 LASER CUTTING

Laser cutting is the process of vaporizing material in a very small, well-defined area. The laser itself is a single point cutting source with a very small point, (0.001" to 0.020" / 0.025mm to 0.5mm) allowing for very small cut widths. The important advantage related to laser cutting are the following:

- There is almost no limit to the cutting path.
- The process is forceless allowing very fragile parts to be laser cut
- Laser beam exerts no force on the part and is a very small spot, the technology is well suited to fabricating high accuracy parts.
- The part keeps its original shape from start to finish.
- The laser beam is always sharp and can cut very hard or brittle materials.
- Sticky materials that would otherwise gum up a blade are not an obstacle for a laser.
- Lasers cutting is at high speeds and cost effective process with low operating and maintenance costs
- Cutting with lasers is a very cost effective process with low operating and maintenance costs
- The quality of machined geometry depends on cut width/hole diameter and taper formation.
- Tapers always exist on laser machined components but it can be minimized. Smaller kerf width or hole diameter reduces the taper.

Sadegh amalnik and Mcguegh [52] developed an expert system for manufacturability evaluation of electrochemical machining. Sadegh amalnik et al., also developed an intelligent system for manufacturability

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evaluation for electrochemical spark machining [53]. In this research an Expert System Approach is used for manufacturability evaluation of Plasma Beam Machining Processes.
This paper addresses the concept of optimization of LBM process by developing an expert system in computer based concurrent engineering environment. The ES links with feature library. The design specification is acquired through a feature based approach. The ES links with material data base which holds attributes of more than 6 types of materials. It also links with Laser data base which hold attributes of 2 types of laser, expert system is also links with Laser machine data base which hold Laser machine parameters.
For each design feature, ES provides information needed for design and manufacturing optimization. The ES can be used as an advisory system for designers and manufacturing engineers. It can be used as a teaching program for new laser operators in computer based concurrent engineering environment, by stimulated emission due to the incident photons of high energy. In Fig. 1 schematic of Nd: YAG laser beam cutting system is demonstrated.

4 EXPERT SYSTEM FOR ND: YAG LBM

An expert system is an interactive intelligent program with an expert-like performance for solving a particular type of problem using knowledge base, inference engine and user interface. In this paper the following step has been used:

4.1. ES for LBM has been developed in a computer based CE environment, the third version of an expert system shell (NEXPERT), based on object-oriented techniques (OOT).

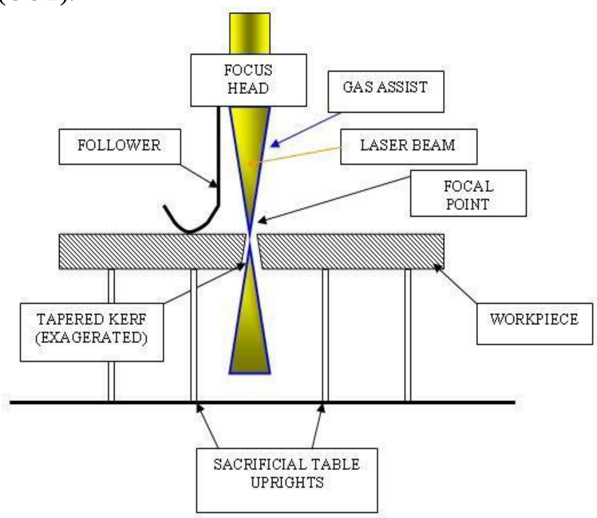

Fig. 1 Schematic of Nd: YAG laser beam cutting system

A Hewlett Packard (HP) workstation was used in development of the ES. A geometric specification of design feature, and material type of the workpiece and its thickness is sent for manufacturability evaluation at the various stages in its design. Within the manufacturability procedure, the machining time and cost of producing part, is estimated. The labour and depreciation cost of LBM for each selected design feature specification, is estimated. Also various machining parameters are estimated.

4.2. The material specification is described in terms of its thickness, width and its melting point etc. The attributes of different material types for LBM, and different type of LBM machine are stored in working memory or data-bases.

4.3. The ES can retrieve information from working memory and advise the designer on the appropriate choice of material, for workpiece, and type of machine.

4.4. The ES also contains information related to good practice rules for LBM and, LBM process capabilities, and constraints.

4.5 For the present ES, knowledge has been gathered from literature and talking with expert and experimental results on LBM.

4.6. For each selected design feature undergoing evaluation for its manufacturability by LBM, the cost of the machine cycle is estimated from those costs for LBM machine depreciation, labour, and machining cost.

4.7. Machine cycle time is also a key factor, which depends for example on setting-up of LBM loading and unloading of work-piece, inspection of component, and general maintenance.

4.8. Assessment of the manufacturability of a workpiece material, usually from machining cycle time and cost, is established automatically by the ES.

4.9. This ES can advise on the manufacturing of each work piece material. From this information, the process variables can be selected so that the best balances between the required quality against efficiency of manufacturing be obtained.

5 ARCHITECTURE OF ND:YAG LBM EXPERT SYSTEM

The ES contains expertise gathered from both experiment and general knowledge about LBM that can be provided to designers and manufacturing engineers. A flow chart of expert system contains the following modules: Material (workpiece) database: The material (workpiece) database contains 10 different material types for work-piece which interactively are acquired by the ES for LBM. Each of which can be produced by LBM machine. Material

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selection is an important stage and a complicated one that is made early in the design process. The direct material cost frequently forms more than 50 per cent of the total product cost [20]. In order to select a material, the system prompts the user to choose between two options for the material selection. The first option is that the user selects to specify the material based on his own criteria. The second one is that the system executes Cambridge Material Selection (CMS) software [55]. CMS is a computer package consisting of a database, a management system and a graphical user interface. The database contains quantitative and qualitative data for a wide range of engineering material: metals, polymers, ceramics, composites and natural materials. With CMS, the most appropriate material will be determined on the basis of previous input of product concepts and requirements. The properties of the candidate material are stored as a data file. Architecture of material selection/costing module is demonstrated in Fig. 2.

A database is a group of cross-referenced data files. These contain all the necessary information for an application. There are four approaches to construct a database, namely the hierarchical, the network, the object-oriented and the relational approaches. Material selection/costing module proposed system was developed using the relational database approach which in turn comprised permanent (static) and temporary (dynamic) databases. The permanent database includes laser beam machine tools and a feature specification database. The databases in the system consist of four separate groups of databases: feature database, material database, machine database, machine parameters databases. In Fig. 3 Architecture of ND: YAG laser beam expert system is demonstrated.

6 EXPERIMENTAL VERIFICATION AND VALIDITY OF THE EXPERT SYSTEM

The expert system (ES) for laser beam machining described above was compared with experimental one. Results are presented in Table 1. These experiments have been carried out on LBM machine. Table 1 demonstrated results of laser cutting and different type of hole making by ND: YAG expert system and experimental ND: YAG laser. An attraction of the laser beam expert system so developed is its capability offering advice to product designers and manufacturing engineers on machining cycle time, and cost, for various machining parameters. The result of the expert system shows machining time and cost for expert system is about 10 percent less than the experimental one.

For example experimental result shows machining time, for rectangular hole 1 minute, but the expert system estimation is 0.89 min. Machining cost, for rectangular hole for experimental is 0.4 UK pound, but for LB expert system is 0.36 UK pound, which is approximately 10 percent less than experimental one.

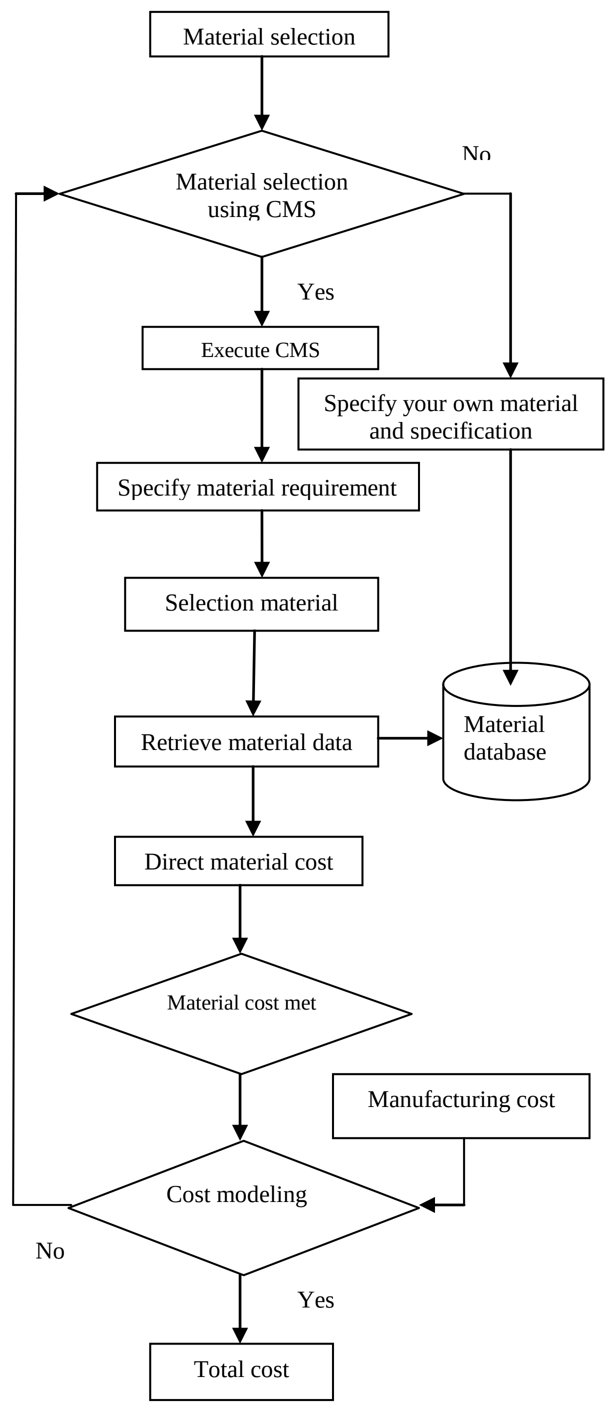

Fig. 2 The material selection/costing module

The cutting speed of experimental is 500mm/min in experimental and 550 mm/min for expert system which is improved approximately 10 percent less than the experimental.

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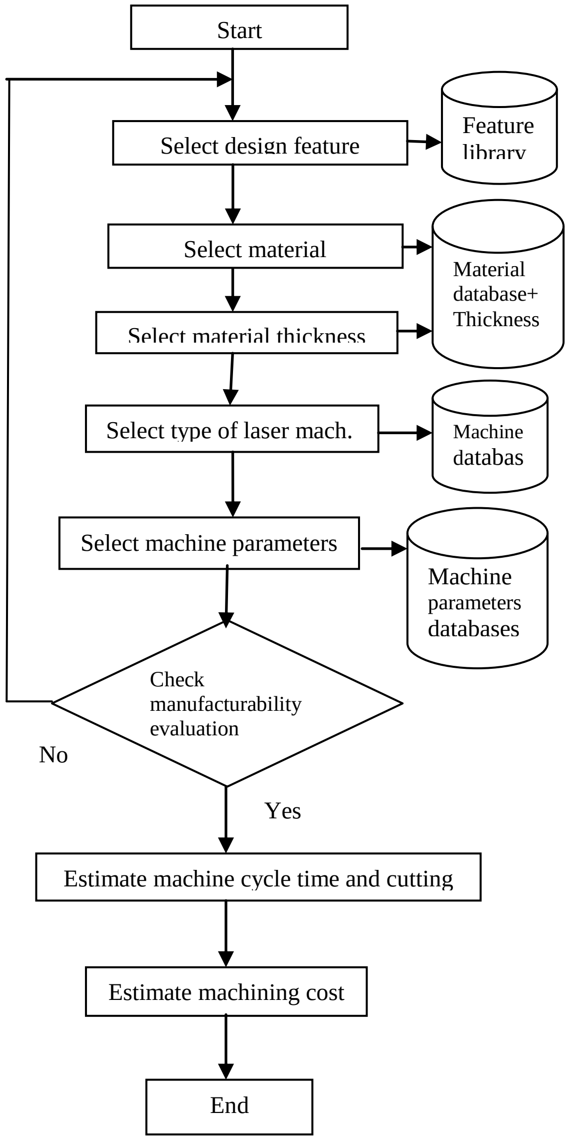

Fig. 3 Architecture of ND: YAG laser beam expert system

7 CONCLUSION

The author has described concept of laser beam machining and its parameters effect on laser beam machining and developed an expert system for ND: YAG laser beam machining process. In this paper, an expert system (ES) was developed for manufacturability evaluation of ND: YAG laser in computer based concurrent engineering. The expert system evaluated machining cycle time and cost in less than 30 seconds. Experimental verification and validity of the expert system is carried out. The results of expert system was compared with the results of experimental laser beam machine**.** Results are presented in tables. The result of the expert system has shown machining cycle time and cost for expert system is about 10 percent less than the experimental one. In addition, material for workpiece was selected by the expert system. It gives valuable information to help designers and manufacturing engineers to improve design and manufacturing. The expert system is linked with design feature library, material database and laser beam machine database. The design specification was acquired through a feature based approach. Material database held attributes of more than 10 types of materials. Laser beam machine database held attributes of 2 types of laser beam machine and machine parameters.

For each design feature, the expert system provided information needed for manufacturability evaluation and estimation of machining cycle time and cost. It could be used for design and manufacturing optimization. The expert system could be used as an advisory system for designers and manufacturing engineers. It could be used as a teaching program for new laser operators in computer based concurrent engineering environment**.** The main direction of future research has been found by the author. Also, various experimental tools used for optimization (such as Taguchi method and RSM) can be integrated together to incorporate the advantages of both simultaneously. Apart from cutting and drilling, it can be concluded from above discussion that LBM is also:

1) suitable for precise machining of micro-parts. The micro-holes of very small diameters (up to 5 μm) with high aspect ratio (more than 20) can be drilled accurately using nanosecond frequency tripled lasers. Cutting thin foils (up to 4 μm) has been done successfully with micro-range kerf width.

2)The laser beam cutting process is characterized by large number of process parameters that determines efficiency, economy and quality of whole process and hence, researchers have tried to optimize the process through experiment demonstrated in Fig. 3. Besides analytical, and artificial intelligent based modeling and optimization techniques for finding optimal and cutting with multi-objective, and with hybrid approach are non-existent in the literature. The two important application areas such as machining of thick materials and machining of micro-parts need considerable research work.

3) Laser Beam Machining process is a powerful machining method for cutting complex profiles and drilling holes in wide range of workpiece materials. However, the main disadvantage of this process is low energy efficiency from production rate point of view and converging diverging shape of beam profile from quality and accuracy point of view.

4) The performance of laser beam machining mainly depends on laser parameters (e.g. laser power, wavelength, mode of operation), material parameters (e.g. type, thickness) and process parameters (e.g. feed rate, focal plane position, frequency, energy, pulse duration, assist gas type and pressure). The important

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performance characteristics of interest for LBM study are HAZ, kerf or hole taper, surface roughness, recast layer, dross adherence and formation of micro-cracks.

Table 1 Comparison of experimental LBM and ND: YAG Laser beam expert system for stainless steel

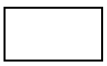
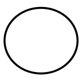
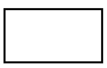
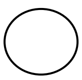
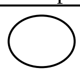
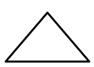
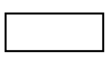
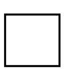
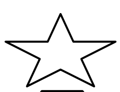
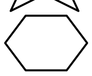
Design feature shape	Design feature type	Feature dimension(mm)	Procedure	Laser power KW	Pulse frequency 100HZ	Laser machining time (min)	Laser Machining cost UK&	Cutting velocity mm/min
	Rectangular hole	width 100, length 150 thick4 mm	Experimental	5	100	1	0.4	500
	Circular hole	diameter 100mm thick4 mm	Experimental	5	100	0.63	0.25	500
	Laser cutting	length 150 thick4 mm	Experimental	5	100	0.3	0.12	500
	Rectangular hole	width 100, length150 thick4 mm	ND:YAG expert system	5	100	0.91	0.36	550
	Cubic hole	diameter 100mm thick4 mm	ND:YAG expert system	5	100	0.57	0.23	550
	Laser cutting	length 150 thick4 mm	ND:YAG expert system	5	100	0.27	0.11	550

Table 2 The expert system results of different design feature for carbon steel material in LBM

Design feature shape	Design feature type	Laser power KW	Pulse frequency 100HZ	Feature descriptions(mm)	Cutting velocity mm/min	Laser machining time (min)	Laser Machining cost UK &
	Circular hole	5	100	dia 100 mm	600	0.52	0.60
	Triangular hole	5	100	Edge 100 mm	600	0.5	0.378
	Rectangular hole	5	100	width 100, length 150	600	0.83	109.38
	Cubic hole	5	100	width 50mm	600	0.33	87.5
	Star hole 10 edge.	5	100	edge size 100 mm	600	1.66	218.75
	Hexagonal hole	5	100	edge 50 mm	600	1	131.25

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