Influence of Process Parameters of Nd-YAG laser Microdrilling on CNT-NiAl Composites

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Abstract

Over the last few decades inter-metallic compounds such as NiAl have been considered as a high temperature structural materials for aerospace industry. A large number of investigations have been reported describing complex fabrication routes, introducing various reinforcing/alloying elements along with theoretical analyses. An approach was offered to synthesize CNT-NiAl intermetallic matrix nanocomposite by Powder metallurgy method. The drilling operation has been carried out using Nd:YAG laser on CNT-NiAl metal matrix composite, which is an important composite in aerospace applications like deep cooling holes on aerospace components. It has been observed that in microdrilling process, circularity of hole at entry, exit, HAZ and taper are important parameters which greatly influence the quality of a drilled hole. Here the effect of various process parameters like lamp current, pulse frequency, pulse width, scanning speed of Nd:YAG laser micro drilling on hole circularity at entry, exit, HAZ and taper has been investigated through response surface methodology (RSM)–based experimental study. The parametric combination for optimal hole circularity, HAZ and hole taper has also been subjected to confirmatory test.

Keywords: Circularity at entry; Circularity at exit; HAZ; Microdrilling; Nd:YAGlaser; Hole taper

1. INTRODUCTION

Composite materials plays a vital role in the field of engineering as well as advance manufacturing to fulfil the specific requirements for various applications like construction, structural, medical, house-hold, transportation, industrial , electrical, electronics, etc. and in response to unprecedented demands from technology due to rapidly advancing activities in aircrafts, aerospace and automotive industries. These materials have low specific gravity that makes their properties particularly superior in strength and modulus to many traditional engineering materials such as metals. As a result of intensive studies into the fundamental nature of materials and better understanding of their structure property relationship, it has become possible to develop new composite materials with improved physical and mechanical properties. Continuous advancements have led to the use of composite materials in more and more diversified applications. The importance of composites as engineering materials is reflected by the fact that out of over 1600 engineering materials available in the market today more than 200 are composite [1].

A large number of investigations have been reported describing complex fabrication routes, introducing various reinforcing/alloying elements along with theoretical analyses . The NiAl intermetallic compounds have attracted industry's attention as potential high temperature light-weight(5.9g/cm^3) materials to replace nickel-base super alloys due to an exceptional combination of high strength and low specific weight, thermal stability, high thermal conductivity (76W/mK) and good oxidation/corrosion resistance upto 1400°C, combined with its ability to retain strength and stiffness at high temperature. The melting point of NiAl was determined by differential thermal analysis (DTA) as1676°C, which is in perfect agreement with the theoretical value(1676°C) obtained from thermodynamic calculations. [2].

NiAl Intermetallic compound has been recognized as one of high temperature structural materials due to excellent physical and mechanical properties such as low density (5.86 gcm-3), high melting point (1911 K) and excellent oxidation resistance up to 1573 K, as well as good thermal conductivity[3,4,5]**.** NiAl compound is also known for its low ductility and fracture toughness at room temperature[6].

CNT'S have been viewed as a promising reinforced phase in composites attributed to their attractive properties(CNTs have High Electrical Conductivity, Very High Tensile Strength, Highly Flexible- can be bent considerably without damage, High Thermal Conductivity, Aspect Ratio, Low Thermal Expansion Coefficient) . The applications of CNTs in metal matrix composites (MMCs), especially Al matrix composites (AMCs), have been widely reported in recent years.

NiAl-CNT intermetallic matrix nanocomposite will be synthesized by powder metallurgy to ensure the effective distribution of carbon nanotubes (CNTs) within the matrix.

A CNC pulsed Nd:YAG laser machining system, manufactured by M/s Sahajanand Laser Technology, India,is used for the experimental study.

Table 1. Details of Nd:YAG laser machining system

Specification	Description
Laser type	Nd:YAG laser
Wave length	1064nm
Mode of operation	Q-switched (pulsed)
Type of q-switch	Acousto-optic Q-switch
Mode of laser beam	Fundamental mode (TEM00)
Mirror reflectivities	Rear mirror 100%, front mirror 80%
Beam diameter 1/e^2	1mm
Laser beam spot dia	100 µm
Average power	75 Watt
Pulse width	120 to 150 ns

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Fig. 1. Nd:YAG laser machine

The system consists of various subsystems such as; laser source and beam delivery unit, power supply unit, radio frequency (RF) Q-switch driver unit, cooling unit, compressed air supply unit, and a CNC controller for X, Y, and Z axis movement. The laser beam is produced by a laser head consisting of Nd:YAG rod and krypton arc lamp which are placed in two different focal points of a gold platted elliptical cavity. The neodymium atoms embedded in yttrium aluminium garnet crystal host is used as lasing medium in Nd:YAG laser. TheNd:YAG crystal is excited by the krypton arc lamp, which is used as the pump source. The amplification of light is accomplished by providing optical feedback with a 100% reflectivity rear mirror, and a front mirror of reflectivity 80%. The Q-switching is an excellent method used in Nd:YAG laser system to produce very short pulse width and very high peak power of laser light from a continuous wave (CW) low power laser. The RF Q-switch driver unit supplies the RF signal to Q-switch for its operation. An intracavity safety shutter is used to block the path of reflection between two mirrors. An aperture, placed inside the cavity restricts the amplification to occur along the off axis of the resonator. The beam delivery system first bends the laser beam at 90, and then focuses it on the work spot through the focusing lens. The main power supply unit controls the laser output by controlling the intensity of light emitted by a krypton arc lamp. The cooling unit consisting of a three-phase chiller unit and a pump, cools the system by circulating the chilled water to avoid thermal damage of laser cavity, lamp, Nd:YAG rod, and Q-switch. A compressed air supply unit has been designed and developed in which compressed air is used as an assist gas.

The CNC controller consists of X-Y-Z axis and a controlling unit named Accupos. One stepper motor is attached to each of the axes and is connected to the controlling unit. This unit can control the axes through a computer. The CNC Z-axis controller unit controls theZ-axis movement of lens. A developed fixture is placed on the Table of the machine to hold the workpiece in a correct position. A charge coupled device camera together with close circuit television (CCTV) monitor is used for viewing the location of workpiece and also for checking the focusing condition of surface of the workpiece. A fixture for holding the workpiece was designed and developed.

2. EXPERIMENTAL DETAILS

2.1 Materials for composite preparation

Commercial grade Nickel-Aluminium alloy powder and Carbon nano tube powder were obtained.

Table 2. Materials with Specification

Material	Specification
Nickel-Aluminium Alloy	Al-50% and Ni-50% , 300 mesh
Carbon nanotube	95% OD: 20-30nm, Length: 10-30μm

2.2 Carbon nanotube functionalization

- 1 gram MWCNT was measured and and was taken in a beaker.
- 30 ml of sulfuric acid and 10 ml of nitric acid (3:1) was added to the one gram MWCNT and the mixture was allowed to undergo sonication process for 24 hours at 40˚C with half an hour interval.
- Then the mixture was diluted with 200 ml distilled water and allowed to cool.
- The mixture was kept one night to settle the MWCNT and filteration was done through whatman 42 paper.
- 16 ml of sulphuric acid and 4 ml of hydrogen peroxide (4:1) was added to the filterated MWCNT in a conical flask and stired at 70˚C for half an hour then it was allowed to cool.
- Then the mixture was diluted with 250 ml of distilled water and water was decanted with a dropper to remove the acid.
- The process was continued several times to remove the acid till minimum amount of CNT solution remain. That CNT solution was centrifuged for several times to remove the acid and separate carbon nanotube.
- Then the pH value was checked time to time to check whether the solution has a pH 6-7. Then the collected carbon nanotube solution was poured on a petridish and kept in oven for one night at 50˚C.
- Then the dried carbonnanotube was grinded with mortar and pestle and and collected in a zipper to keep the functionalized MWCNT away from moisture.
- As functional groups are added, so the mass of carbon nanotube is increased from 1 gram to 1.5 gram. And both sides of carbon nanotube is opened and it is ready to be bonded with matrix material.

2.3 Preparation of sample by powder metallurgy method

The MMC test specimens are fabricated by powder metallurgy route using ball mill mixing, solid state sintering.

2.3.1 Mixing of powders

The MMC test specimens are fabricated by the powder metallurgy route adopting the usual mixing and solid state sintering. Nickel-Aluminium powder and carbon nanotube by weight % are mixed for fabricating the composite. Total three categories of mixture were prepared (NiAl + 0 % CNT, NiAl + 0.5% CNT, NiAl + 1 % CNT). Blending is carried out in ball planetary mill (Model- Planetary Ball Mill PM 100 , Make-RETSCH, Germany). Planetary Ball Mills are used wherever the highest degree of fineness is required.

Ball to Powder ratio= 20:1 that means for 1 gram powder ball required = 20 gram

Weight of one steel ball= 0.98 gram

So, no of steel ball required for 1 gram powder = 21

Apart from the classical mixing and size reduction processes, the mills also meet all the technical requirements for colloidal grinding and have the energy input necessary for mechanical alloying processes. The extremely high centrifugal forces of the Planetary Ball Mills result in very high pulverization energy and therefore short grinding times.

The PM 100 is a convenient benchtop model with 1 grinding station. It consists of two cylindrical containers of chrome steel. The blending machine continues rotations for 240 revolutions per minute to reach a homogenous distribution of the reinforcement in the mixture.

2.3.2 Compaction of the powder mix

From 20 gms of the powder mixture 1.2 gram mixture was taken for compaction in a cold uniaxial press in a metallic die-punch arrangement to make one pallet.

2.3.3 Cold uniaxial pressing

The powder sample is pressed in the cold uniaxial pressing machine (Make-Specac,Type-Hydraulic) to render the green circular test samples of 12mm outer diameter applying aload of 6 ton, which accounted 1200 bar pressure. A stainless steel die of 12 mm internaldiameter was used for this purpose. To allow the powder to flow freely and to prevent thespecimen from sticking on to the walls, Polyvinyl Alcohol (PVA) was used as a binder that was applied tothe walls of the die and punch.

When the load was given 5 ton then the compacted samples found out in powder form after some time. When the load was given 7 ton fracture was seen on the top surface of the compact.

2.3.4 Sintering of the green samples

After cold compaction, sintering was done in a muffle furnace at an elevated temperature of 900 deg cel for 2 hours in a controlled atmosphere environment but just below the melting point of major constituent for a sufficient time. It is carried out in horizontal muffle furnace (Make-Naskar and Co., Type-Vacuum and Control Atmosphere) .

After 2 hours the samples were undergone furnace cooling as it gives better result than normilizing.

The sintered samples prepared by the above discussed process are shown in Figure These green samples are ready for further use. The properties of the samples were then measured by different measuring equipment.

2.4 Design of Experiments

The most important step in the DOE lies in the selection of the control factors and their levels. LBM process has large number of process related parameters which are defined below. Based on initial trials and exhaustive literature review [7,8,9,10**]** four machining parameters namely, Lamp current, Pulse frequency, Pulse width, Speed are choosen. Laser beam microdrilling operation has been performed on the carbon nanotube reinforced NiAl metal matrix composite workpiece having a mean thickness of 2.9 mm.. Based on literature survey and preliminary investigations, four parameters have been chosen as inputs: lamp current, pulse frequency, pulse width, and scanning speed. Selection of the range of process parameters setting has been made after performing some pilot experiments using fixed job thickness and type of air pressure.

Table 3 Control parameters and their levels

Control parameters	Levels		
	Low	Med	High
Lamp current(Amp)	22	23	24
Pulse frequency(kHz)	1	2	3
Pulse width(%)	6	9	12
Speed	80	100	120

A total of 27 sets of experiments have been carried out according to the box-behnken design based on RSM.

Fig. 2. Laser microholes on samples

After performing 27 experiments the entry hole diameter of the hole, exit hole diameter of the hole and heat affected zones are calculated using a scanning electron microscope.

3. RESULTS AND DISCUSSIONS

Entry hole diameter, Exit hole diameter, Taper, Heat affected zone which is obtained from SEM results with respective combinations are given in the Table 4.

3.1 Effects of process parameters on circularity

Circularity is the ratio between two diameters so it is unit less. As the laser machining is based on the interaction of a laser beam with workpiece surface, maintaining high hole circularity is a difficult task in microdrilling operation.

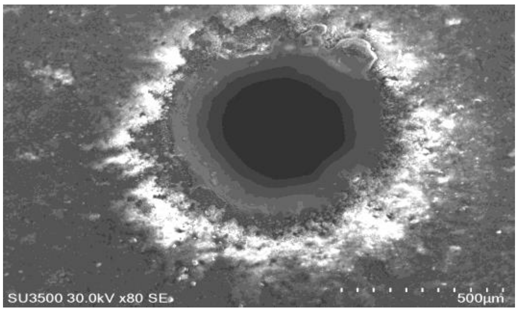

Fig. 3. Entry hole diameter

Table 4 Input parameters with output results

Current	Frequency	Width	Speed	Entry hole dia(μm)	Exit hole dia(μm)	Width of HAZ	Taper(rad)
23	3	9	120	738	316.5	129	4.1596
24	2	9	120	591.5	260	103	3.2747
24	3	9	100	680.5	202	130	4.7269
22	1	9	100	665	196	85.5	4.6329
23	2	9	100	701	376.5	219	3.2055
23	2	6	120	686.5	387	185	2.9585
22	2	9	80	637	242.5	151	3.897
22	2	6	100	614	205	183	4.0403
23	2	9	100	692	321.5	155	3.6599
23	2	9	100	746	313.5	170	4.2724
24	1	9	100	708.5	177	161	5.2504
22	2	9	120	603.5	209	225	3.897
23	3	12	100	701.5	378.5	147	3.1907
23	2	12	80	702	405	69.5	2.9338
23	3	6	100	677	392	137	2.8153
22	3	9	100	619	291	81.4	3.24
24	2	6	100	586.5	298	165	2.8498
24	2	9	80	662.5	272	143	3.8575
23	1	9	80	705	166.5	143	5.3195
23	1	12	100	683	256.5	190	4.2131
24	2	12	100	728	318	104	4.0501
23	1	9	120	627	136	149	4.8503
23	2	6	80	738	295	174	4.3761
22	2	12	100	680.5	280	244	3.9563
23	1	6	100	650.5	185.5	105	4.5935
23	2	12	120	606.5	264	43.8	3.3833
23	3	9	80	733	269	228	4.5836

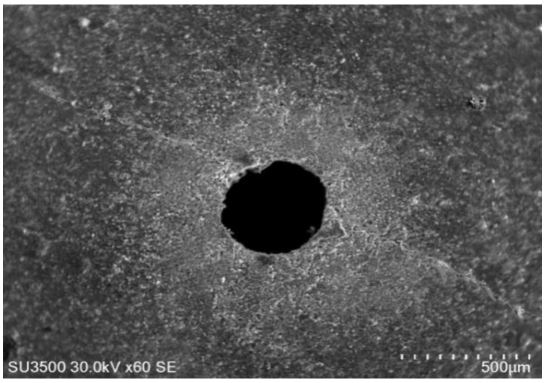

Fig. 4. Exit hole diameter

At entry:

In general, Circularity increases with an increase in pulse width and also affects the edges of the hole at entrance. At high pulse width, energy received by the surface becomes very low and insufficient to remove material from the top surface, as a result of which low circularity is produced.

Initially when pulse frequency increases, pulse-off (time between two successive incidents of laser beam) time becomes shorter, and the beam energy generated becomes lower, as a result material gets melted and solidified with less agitation and disorder and higher circularity is formed. After a certain limit when pulse frequency increases, then the pulse-off time becomes very short and the molten material does not get time to be solidified. Due to which agitation and disorder takes place in the molten material during material removal process and result in a lower circularity.

The amount of molten material is higher at high lamp current, and some material may get adhered to the edge of hole due to re-solidification at high air pressure, and a hole of lower circularity is produced. It is also observed that at low air pressure lamp current has less effect on hole circularity at entry. We can say the the abovesaid theories for only one response factor with one process parameter but when a combination of process parameters is coming into picture then we are getting values beyond of the theory.

Here at pulse width 6 % , frequency 2 kHz, speed 120 ms-1 and current 24 amp minimum diameter 586.5 μm was achieved.

At exit:
When lamp current increases, the energy of laser beam also increases which in turn increases the material removal from the entire cross-section of the workpiece, due to which circularity improves at exit. This is due to the fact that higher lamp current generates higher thermal energy; as a result, large volume of material is melted from the entire thickness of the workpiece.
Circularity first increases and then decreases following a parabolic curve with change in pulse frequency. Initially, when pulse frequency increases, pulse-off time becomes shorter, and the beam energy generated becomes lower, as a result of which the material gets melted and solidified with less agitation and disorder and produces higher circularity. After a certain limit when pulse frequency again increases, the pulse-off time becomes very short, and the material does not get time to be solidified, due to which agitation and disorder takes place in molten material during material removal process, and it results in a lower circularity.
Here at pulse width 12 % , frequency 2 kHz and current 23 amp, speed 80 ms-1 maximum diameter 405 µm was achieved.

3.2 Effects of process parameters on heat affected zone

The use of laser micro-drilling or micro-machining in manufacturing industry can be recognized through several advantages mostly small heat-affected zone (HAZ). The width of HAZ was calculated using scanning electron microscope.

Heat affected zone must be minimum for better quality purpose. In this experiment for combination of 23 amp current, 2 kHz pulse frequency, 12 % width and 120 scanning speed minimum width of heat affected zone was found minimum i.e 43.8 µm.

3.3 Effects of process parameters on hole taper

In order to measure the taper, the diameter of the drilled holes at entry and exit were also measured from the microscopic views of holes at entry and exit.
Due to the focusing characteristics of laser beam, it is very difficult to produce holes without taper. But from the manufacturing point of view, it is desirable to make the drilled holes circular and without taper.
The hole taper is calculated as:

$$\text{Hole Taper (rad)} = \frac{\text{Hole entrance diameter} - \text{Hole exit diameter}}{2 \times \text{Thickness of the workpiece}}$$

Entry hole diameter and exit hole diameter which is obtained from SEM results with respective combinations were found out and by using abovesaid formula the hole taper values are calculated and shown above.
When pulse frequency increases, the pulse off time decreases, and as a result, the excessive number of pulses break through the material, increases the hole diameter at exit, and produces a lower hole taper. It can also be said that the hole taper first decreases at the initial levels of lamp current and then increases with increase in lamp current significantly at all levels of pulse frequency. At high lamp current, heat generation is high, and as a result, the top surface of the workpiece, where the laser beam is focused, gets melted and vaporized instantly, and a large amount of material is removed from the top surface during the formation of the hole, which results in a large entrance hole diameter and large hole taper.
But when set of process parameters combinations came into picture then; for combination of 23 amp current, 3 kHz pulse frequency, 6 % width and 100 ms-1 scanning speed minimum heat affected zone was found i.e. 2.8153 deg.

3.4 Confirmation Test

The last step in the application of Taguchi's parameter design is to conduct the confirmatory experiment.

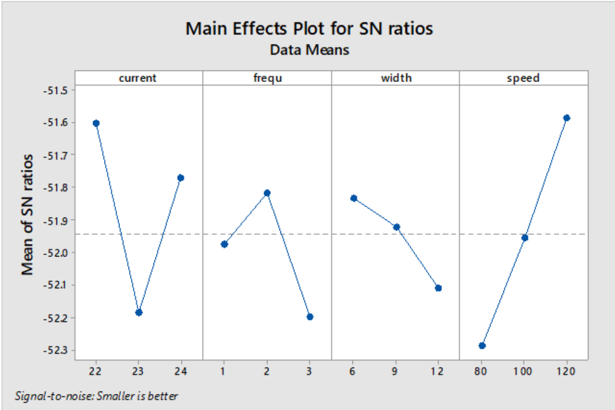

Fig. 5. Optimal set of parameters obtained through Taguchi design

With these values of process parameters we are getting minimum entry hole diameter, low HAZ, and low taper.

The optimised parameter settings are lamp current of 23 amp, pulse frequency of 3 kHz , Width 12% and Speed 80 for achieving the predicted maximum value hole circularity at entry 605 µm of 0.9382 and Length of Haz 28 µm Taper 3.0149.

W e can observe a remarkable decrease in heat affected zone where as slight increase in taper and entry hole diameter is negligible.

4 CONCLUSIONS

In the present research, pulsed Nd:YAG laser-drilling of CNT-NiAl composite has been carried out, and effects of different process parameters on response variables have been explained in detail.

This work concludes:

1. Processing of CNT- NiAl composite by powder metallurgy method was carried out.

2. Characterization of the composite material was done. Microstructure was checked and hardness was measured.

3. Laser microdrilling of the MMC was performed successfully and effect of various process parameters, i.e. lamp current, pulse frequency, pulse width, speed on hole circularity at entry and exit , HAZ and hole taper was discussed.

4. Analysis of experimental results using Taguchi method was done.

5. Optimum parameters for overall improvement in machining process was reported.

6. It can be concluded that various process parameters, i.e., lamp current, pulse frequency, pulse width, speed can be controlled for achieving responses like hole circularity at entry and exit, HAZ and hole taper of desired value by using the developed mathematical model based on RSM.

The work as described above was carried out on a new class of material. The findings were also encouraging with respect to the performance of the material. It can be suggested that the material can find applications mostly in aerospace and automobile industries. Also the prepared intermetallic compound shall have a lot of research potential.

References

[1]. Manocha L.M. and Bunsell A.R., (1980), Advances in composite materials, , Pergamon Press, Oxford, pp. 7-21.

[2]. Bochenek Kamil, Basista Michal , (2015). ―Advances in processing of NiAl intermetallic alloys and composites for high temperature aerospace applications‖ in:ELSEVIER.

[3]. Gennari S., Maglia F., Anselmi-Tamburini U., Spinolo G. (2003), Intermetallics 11 1355e1395.

[4]. Hu W., Weirich T., Hallstedt B., Chen H., Zhong Y., Gottstein G. (2006), Acta Mater 54 2473e2488.

[5]. Liu E., Jia J., Bai Y., Wang W., Gao Y., Mater. Des. (2014) 53 596e601.

[6]. Geist D., Gammer C., Rentenberger C., Karnthaler H.P., (2015) J. Alloys Comp. 621 371e377.

[7]. Priyadarsini M., Pattnaik S.K., Mishra D., Panda S. (2015) ―Multi Characteristics Optimization of Laser Drilling Process Parameter Using Grey Fuzzy Reasoning Method‖ Pp 1518 – 1532

[8]. Shadakshari R, Mahesha k, Niranjan H B, (2012). Carbon Nanotube Reinforced Aluminium Matrix Composites – A Review‖, Vol. 1, Issue 2

[9]. Thawari G., (2005) , ―Influence of process parameters during pulsed Nd:YAG laser cutting of nickel-base superalloys‖ in: Journal of Materials Processing Technology 170 229–239.

[10]. Biswas Ranjib , Kuar A. S., Biswas S. K., Mitra S., (2010) ,Effects of Process Parameters on Hole Circularity and Taper in Pulsed Nd:YAG Laser Microdrilling of Tin-Al2O3 Composites