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A parametric study of pulsed Nd:YAG laser micro-drilling of gamma-titanium aluminide

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ABSTRACT

In the present research, Nd:YAG laser micro-drilling of gamma-titanium aluminide, a new material which has performed well in laboratory tests as well as in different fields of engineering, is studied. The effect of different process parameters in the optimization of the process is investigated. The aspects considered are the hole circularity at exit and the hole taper of the drilled hole. Lamp current, pulse frequency, air pressure and thickness of the job are selected as independent process variables. The central composite design (CCD) technique based on response surface methodology (RSM) is employed to plan the experiments to achieve optimum responses with a reduced number of experiments.

1. Introduction

A comprehensive modelling and optimization of the laser micro-drilling of gamma-titanium aluminide has been carried out. Gamma-titanium aluminide (Ti—44.5 at%, Al—2 at%, Cr—2 at%, Nb—0.3B at%), is a new alloy that has already performed well in laboratory tests as well as in turbine blades, engine valves, seal supports, cases, metal cutting tools, missile components, nuclear fuel and artificial joint prostheses. The room temperature mechanical properties of the alloy in its primary annealed condition are exhibited in Table 1. It is very suitable for structural applications and is likely to replace the Ti–Ni-based super alloy in the temperature range 400–800 °C. This material is becoming important in the manufacture of components in technologically advanced industries such as nuclear reactors, automobiles, electronics, aerospace etc. due to its superior properties such as high temperature-strength retention, high thermal conductivity, low density, high yield and ultimate tensile strength, very high hardness, very low density, good creep and oxidation resistance. Despite its remarkable properties, it is a considerable challenge to process the material using conventional machining due to its extreme brittleness and low fracture toughness at room temperature. Different aspects of the machining of this alloy have been investigated by several researchers [1–3]. However, no comprehensive research work has been reported in the field of laser micro-drilling of this alloy. No technology guidance is available for laser micro-drilling of such useful materials in industry. Thus, for effective utilization of this material in modern manufacturing industry, knowledge of micro-hole drilling is required.

Pulsed laser drilling has progressed remarkably over the years to become an essential tool for micro-hole drilling in many components used in the technologically advanced industries. The basic material removal mechanism in laser drilling is based on the absorption of laser energy from a series of laser pulses at the same spot [4,5]. Material is melted and ejected to form a hole. The use of laser micro-drilling or micro-machining in manufacturing industry can be attributed to several advantages like high production rate, applicable to both conductive and non-conductive materials, no mechanical damage or tool wear due to non-contact processing, improved product quality, low material wastage, low production cost, small heat affected zone (HAZ), and ecologically clean technology. A pulsed Nd:YAG laser produces high intensity infrared radiation at a wavelength of 1.06 μm, with output powers ranging from 500 to 12,000 W. Due to its short wavelength (compared with CO_2 lasers), it enables processing of highly reflective materials with less laser power [6].

Taper formation and production of non-circular holes are characteristic of the laser micro-drilling operation, as laser machining is based on the interaction of a laser beam with inherent focusing characteristics [7]. But it is desirable to make the drilled holes circular and with no taper. Modelling of the process is required to be able to control these two important characteristics. Developing a physical model for laser percussion drilling is very complicated since a large number of parameters control the process. Some prior studies have used statistical

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Table 1
Properties of gamma-titanium aluminide.

Property	Unit	Value
Yield strength	MPa	463
Ultimate tensile strength	MPa	499
Modulus of elasticity	MPa	144
Poisson's ratio	–	0.24
Elongation	%	0.55
Density	g/cm^3	3.76

modelling to analyse and determine optimal parameter setting of the process. Kuar et al. [8] experimentally investigated the influence of laser machining parameters on the heat affected zone thickness and phenomena of tapering during CNC-pulsed Nd:YAG laser micro-drilling of zirconium oxide (ZrO_2) and performed parametric analysis through response surface methodology (RSM). In another study, Kuar et al. [9] investigated the effect of several laser machining parameters on HAZ thickness and taper of the micro-drilled holes on alumina–aluminium composite. Ghoreishi et al. [10] employed a statistical model to analyse and compare hole taper and circularity in laser percussion drilling on stainless steel and mild steel. Jackson and O'Neill [11] investigated the interaction phenomena of Q-switched, diode-pumped Nd:YAG laser using different wavelengths on M2 tool steel. Yilbas and Yilbas [12] used a statistical method to investigate the effects of the variation of single-pulse laser drilling parameters on the hole geometry for Nimonic 75 workpiece material by using a full factorial design to identify the main and first-order interaction effects on the hole quality in single-pulse drilling including re-solidified material, taper, barrelling, inlet cone, exit cone, surface debris and mean hole diameter. Yilbas [13] examined four materials nickel, tantalum, EN 58 B and titanium to obtain laser drilling speed using a statistical analysis. In another study, Yilbas [14] conducted drilling experiments on three materials, stainless steel, nickel and titanium, using single-pulsed laser beam. Bandhopadhayay et al. [15] investigated the influence of the process variables on hole diameter and taper angle of drilled holes produced on thick IN718 and Ti-6Al-4V sheets by Nd:YAG laser. French et al. [16] used two level factors in Nd:YAG laser percussion drilling to find the significant factors from a list of 17 factors. The main effects of factors and first- and second-order interactions were analysed and it was found that pulse shape, energy, peak power, focal position, gas pressure and Nd:YAG laser rod were the most significant influences on the hole taper and circularity. In addition to statistical analysis of hole taper, some recent efforts have also been made to control hole taper via the development of drilling techniques [17,18]. Almeida et al. [19] investigated the effects of Nd:YAG laser machining on quality and formation of phases in the cut surface on commercially pure (CP) titanium (grade 2) and Ti-6Al-4V (grade 5) sheets. The process parameters were investigated using factorial.

In the present research, an experimental investigation into pulsed Nd:YAG laser micro-drilling of gamma-titanium aluminide has been carried out. A central composite design (CCD) and response surface method have been used to analyse the effect of the four major laser micro-drilling process parameters i.e., lamp current, pulse frequency, assist air pressure and thickness of the job. Two geometrical features, the circularity of the hole at exit and the hole taper are considered and modelled using a statistical approach. The evolution of the heat affected zone is also an important hole characteristic during laser beam machining, but it is not included in the present research as HAZ does not formed appreciably and does not vary with changes in laser parameter settings. This may be due to the higher thermal diffusivity of gamma-titanium aluminide. It is observed that when diffusivity is high, the material cools at a faster rate and the HAZ becomes small. The diffusivity is proportional to thermal conductivity and inversely proportional to the density. As thermal coductivity of the material used is high and density is low, the diffusivity of this material is very high. Compressed air was used during the laser drilling process, which also helps to reduce the size of heat affected zone. Multi-response optimization analysis has also been carried out using MINITAB.

2. Nd:YAG laser system used for micro-drilling operation

A pulsed Nd:YAG laser-based CNC machining system, manufactured by M/s Sahajanand Laser Technology, India, is used for the experimental study. The detailed specification of the setup is listed in Table 2. The system consists of various subsystems such as the 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 output from the Q-switched Nd:YG laser is directed to the workpiece using a beam delivery system that 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 assist gas is required mainly to remove the machined particle from the machined zone. The compressed air, after coming out form the compressor, had significant moisture content that was removed by the moisture separator. A valve was attached to the moisture separator to remove the water droplets before machining started. The supply line of the compressed air passes through the moisture separator and was connected to the pressure (regulatory) valve to supply compressed air at various pressures to the laser machining zone.

The CNC controller consists of *X*–*Y*–*Z*-axis translation stage and a control unit. A stepper motor is attached to each of the axes and this is connected to the controlling unit. The CNC *Z*-axis controller unit controls the *Z*-axis movement of the focussing lens. The workpiece was held on the table of the machine. A CCD camera together was used for viewing the location of the workpiece and for checking the focusing of the laser beam on the surface of the workpiece. The photographic view of the pulsed Nd:YAG laser-based CNC machining system is shown in Fig. 1.

Table 2
Specification details of Nd:YAG laser machining set-up.

Specification	Description
Laser type	Nd:YAG laser
Wave length	1064 nm
Mode of operation	Q-switched (pulsed)
Type of Q-switch	Accousto optic Q-switch
Mode of laser beam	Fundamental mode (TEM_{00})
Mirror reflectivities	Rear mirror100%, Front mirror 80%
Beam diameter $1/e^2$	1 mm
Laser beam spot diameter	100 μm
Average power	75 W
Pulse width	120–150 ns