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Geometrical features and metallurgical characteristics of Nd:YAG laser drilled holes in thick IN718 and Ti–6Al–4V sheets

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Abstract

Laser drilling is increasingly becoming the method of choice for precision drilling of a variety of components, particularly in the aircraft industry. Notwithstanding the current level of acceptance of laser drilling in the aerospace industry, a number of defects such as spatter, recast and taper are associated with laser drilled holes and elimination of these defects is the subject of intense research. The present paper deals with Nd:YAG laser drilling of 4 and 8 mm thick sections of IN718 and Ti–6Al–4V materials. The influence of type of material and its thickness, as well as parametric impact of key process variables like pulse frequency and pulse energy, have been determined. In the course of this study, relevant geometrical features of the drilled holes, like hole diameter and taper angle, have been comprehensively investigated. In addition, all metallurgical characteristics of interest, viz extent and nature of spatter, recast and heat-affected zone, have been evaluated. Effort has also been made to obtain some insights into the evolution of a through-thickness hole during laser percussion drilling of thick sections by careful experimentation involving monitoring the progression of the drilled hole with increasing number of laser pulses. Issues pertaining to variation of taper with depth of hole, change in crater depth with progressive drilling and specific energy consumption are also discussed.

Keywords: Laser drilling; Hole quality; Taper; Spatter; Recast layer; Heat-affected zone (HAZ)

1. Introduction

Over the years, the laser drilling technique has progressed remarkably to become the method of choice for meeting a vast majority of potential industrial requirements for micro-hole drilling in such diverse components as watches, turbine blades and circuit boards [1]. The aerospace industry, in particular, has been employing this technique with success for drilling large number of closely spaced cooling holes in turbine engine components like airfoils, nozzle guide vanes and combustion chambers [2–4]. The ability of the laser to drill high aspect ratio holes in a non-contact manner, yielding acceptable hole quality and reproducibility at very high processing speeds, has been perceived to be an overwhelming advantage. However, the drive to continuously enhance the overall efficiency of aero-engines is imposing more stringent demands on cooling hole quality. Consequently, greater attention is now warranted to ensure that specifications pertaining to hole quality, in respect of both geometrical characteristics (viz hole size, taper and aspect ratio) and metallurgical characteristics (viz heat-affected zone, recast layer and micro-cracking), are satisfactorily met. Notwithstanding the promise of laser drilling as well as its current level of acceptance by the aerospace industry, it is widely documented that a number of defects such as spatter (re-solidified material around the hole periphery), recast (material accumulated on the hole side-wall), and taper (non-cylindrical nature of the hole) are inherently associated with the laser drilling process [5–7]. Prior work has amply revealed that optimizing the laser parameters such as average power, pulse energy, pulse duration, pulse frequency, focal position etc. can possibly provide a means for minimizing the above defects [8,9]. As a result, a good deal of attention is now being devoted to assessing parametric impact of key process variables in an effort to optimize the process to achieve best hole quality.

Of the three approaches to laser drilling, namely single pulse, percussion and trepanning [10], the first two are the most popular for producing aero-engine quality holes and, consequently, are the most widely investigated. Yilbas [6] has shown that the extent of taper formation during laser percussion drilling of thin sections can be significantly

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reduced by suitable control of laser variables. His work has further revealed that optimization of parameters like focal position, pulse energy, pulse width and pulse frequency can effectively control recast layer formation inside the drilled hole. Normally, a high peak power is desirable to promote material removal by vaporization rather than melting, and the high vapor pressure generated in the process also serves to efficiently eject molten material, thereby suppressing formation of recast layer [5]. In this context, prior work suggests that the required peak power should be preferably obtained by appropriate control of pulse energy and pulse duration. Studies by Yeo et al. [5] and results reported by Chen et al. [11] indicate that an excessively long pulse duration or a very high pulse energy can both lead to deformation of parent material structure as well as adversely influence taper and recast layer formation. Other research efforts have established that a shorter pulse duration minimizes the recast layer and reduces micro-cracking at the sidewalls of the laser drilled hole [12,13], with a pulse duration of 0.1–2.5 ms being proposed as being most suitable for deep hole drilling [5]. There has also been an initiation of efforts aimed at tailoring the pulse pattern to enhance hole quality and this has yielded encouraging results [14–16]. Several methods involving application of anti-spatter coatings [17,18], as well as drilling in transparent media [19], have also been experimented with to minimize spatter formation.

The above research efforts have made significant contributions to the existing level of knowledge in the field of laser drilling. However, a vast majority of prior studies have been devoted to laser drilling of thin sections. The evolution of a through-thickness hole during laser percussion drilling is also not fully understood. In view of the above, the present paper deals with laser drilling of thick sections of IN718 and Ti–6Al–4V alloys to assess the influence of type of material and its thickness, as well as to determine the parametric impact of process variables like pulse frequency and pulse energy on the quality of drilled holes. Both geometrical and metallurgical characteristics of the laser drilled holes have been comprehensively investigated. An effort is also made to monitor the evolution of a hole during percussion drilling and gain some insight into issues such as taper, recast formation, specific energy requirement for drilling etc.

2. Experimental

2.1. Laser drilling experiments

Laser drilling experiments were performed with a 400 W Nd:YAG laser (Model JK704) from GSI Lumonics, UK, emitting 1.06 μm wavelength with fixed beam delivery. The laser was operated in the low divergence (LD1) tuned resonator configuration suitable for drilling. The laser beam was focused with a 120 mm focal length lens, giving a spot size of approximately 0.24 mm diameter. A co-axial gas nozzle assembly equipped with the lens was used to provide an assist gas for drilling through a conical Teflon nozzle with a 1.5 mm diameter orifice. Oxygen and nitrogen were employed as assist gases during processing of IN718 and Ti–6Al–4V, respectively. All drilling experiments were carried out in the percussion drilling mode and holes were drilled normal to the surface.

In view of the current interest in nickel-base superalloys as well as titanium alloys for aerospace applications, IN718 and Ti–6Al–4V materials were employed for laser drilling experiments during the present study. In case of both materials, flat sheet specimens of two different thicknesses (4 and 8 mm) were used in the study to simultaneously assess the influence of material type and thickness on quality of drilled holes. Laser drilled samples were generated for different material-thickness combinations by varying the pulse energy and pulse frequency. However, the focal position was kept on the material surface and pulse width was kept constant at 0.7 ms throughout the experiments. The ranges over which the above key process variables were varied during experimentation are shown in Table 1. While all 4 mm thick materials could be drilled by a single shot, thicker 8 mm materials were drilled in the shutter open-shutter close mode, with the shutter being kept open until the material was drilled through. In order to better understand the progression of the drilled hole during percussion drilling, a separate set of experiments was also carried out on 8 mm thick specimens of both IN718 and Ti–6Al–4V materials by progressively increasing the number of pulses until ‘‘total drill through’’ was achieved. The ‘‘total drill through’’ was considered to have been achieved when the laser pulse, and the accompanying material expulsion, was visible from the exit-side of the material being drilled, through the safe-viewing special-glass window provided in the workstation enclosure. Single pulse increments during the carefully executed experiment ensured that the data pertaining to the total number of pulses required for total drill through as reported herein was highly reliable. In each case, this was further verified by drilling the sheet using a pulse train with pre-set number of pulses (determined as indicated above) in the percussion drilling mode.

2.2. Characterization

All laser drilled holes were extensively characterized to determine the geometrical and metallurgical characteristics

Table 1
Parameters employed for laser drilling experiments

Parameter	Value/range
Pulse width	0.7 ms
Pulse energy	7.5–15 J
Pulse frequency	4–9 Hz
Focus position	At surface
Nozzle stand off	4 mm from material surface
Assist gas	Oxygen at 4×10^5 N m^{-2} for IN718, nitrogen at 14×10^5 N m^{-2} for Ti–6Al–4V

of each hole and ascertain the process parameter impact therefrom. The surface morphology of the laser drilled holes, as well as spatter formation, was studied using a scanning electron microscope (SEM) (Model JSM-5410, JEOL, Japan). Elemental analysis of the spatter was carried out utilizing an energy dispersive spectrometer (EDS) attachment available with the SEM. The spatter was subsequently removed by light polishing using a coarse emery paper and the inside of the hole was cleaned of any debris resulting from such polishing by an ultrasonic cleaning system to facilitate accurate measurement of the entry-side and exit-side hole diameters. The hole size measurements were performed using an optical microscope (Lieca, UK). A total of four diameter measurements were made at hole orientations 45° apart and averaged values have been reported herein. Based on entry-side hole diameter (d_{entry}) and exit-side hole diameter (d_{exit}) measurements, the non-cylindricity or taper was calculated using the expression:

$$\mathrm{Taper}(\theta) = \tan^{-1}[(d_{entry} - d_{exit})/(2t)] \quad (1)$$

where θ is the taper angle and t the material-thickness.

After completion of geometrical measurements, the laser drilled samples were sectioned using a slow speed saw, mounted and sequentially ground to the hole center. For some selected samples, hole diameter measurements were carried out on mounted cross-sections at 1 mm depth intervals from the drilled hole surface to investigate the evolution of taper and its variation with depth. To reveal the metallurgical characteristics of the drilled hole, all samples were polished finely with 0.5 μm diamond paste. The samples were then etched to reveal the heat-affected zone (HAZ) and recast layer microstructures. Ti–6Al–4V samples were etched with a 1:1:8 HNO_3–HF–CH_3OH solution whereas a 2:3:6 H_3PO_4–H_2SO_4–H_2O mixture was used as etchant for the IN718 samples. SEM was used for investigation of recast layer and HAZ microstructure while the EDS technique was used to determine the elemental compositions in these regions. A dynamic ultra-microhardness tester (Model DUH-202, Shimadzu, Japan) was employed to carry out microhardness measurements on the recast layer and HAZ at very low load (50 g).

3. Results and discussions

As previously indicated, attention was devoted during the present study to comprehensively assessing the influence of laser drilling parameters identified as being critical, namely pulse frequency and pulse energy, on the geometrical and metallurgical features observed in the drilled holes. The above laser parameters were varied over a reasonably wide operating window to drill both IN718 and Ti–6Al–4V materials of different thickness to obtain representative trends in hole quality variation with type of material and its thickness, as well as due to variation of each laser parameter.

3.1. Geometrical characteristics

The geometrical features of every laser drilled hole generated during the present study were carefully investigated. This included measurement of entry and exit-side hole diameters for each hole and calculation of taper angle based on the above measurements. The prominent results are briefly discussed below.

3.1.1. Influence of material and thickness on hole diameter

The typical variation in entry-side hole diameter with type of material and its thickness, for a specific set of laser drilling parameters, is indicated in Fig. 1. It should, however, be pointed out that the results, in fact, depict the combined effect of the material type and assist gas chemistry on the laser drilling process, since different assist gases were employed for drilling of IN718 and Ti–6Al–4V materials during the study. In case of both 8 and 4 mm sheet drilling, processing of Ti–6Al–4V with N_2 gas assist yielded larger holes than IN718 drilling with O_2 gas assist. It is pertinent to mention here that earlier work by Bostanjoglo et al. [20] on laser drilling of stainless steel has also shown that the use of relatively more reactive oxygen in place of compressed air, under identical gas pressure, yields smaller entrance diameters. A similar result has also been reported by Lusquinos et al. [21] during laser drilling of slate. As far as the present study is concerned, it is believed that the exothermic heat of reaction when O_2 is used as assist gas for drilling IN718 significantly enhances the total energy available for drilling and, thereby, increases the contribution of vaporization to the material removal process during hole formation. As a result, erosion of the hole walls by ejecting molten material is substantially reduced and leads to a smaller hole diameter.

Another interesting observation based on the results depicted in Fig. 1 is that d_{entry} decreases with increasing material-thickness in case of both IN718 and Ti–6Al–4V. While this finding is contrary to results reported in the literature [5,6] as well as those obtained in this laboratory during laser drilling of thinner materials (<3 mm thickness)

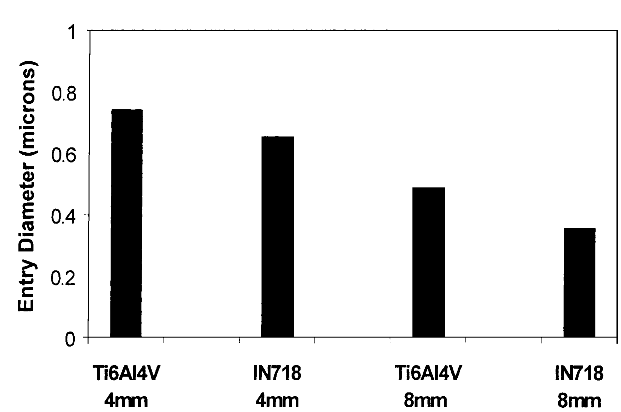

Fig. 1. Influence of material and thickness on entry diameter of laser drilled holes (pulse width: 0.7 ms, pulse energy: 15 J, pulse frequency: 9 Hz).

[22], the above trend was consistently noted during drilling studies on 4 and 8 mm thick materials conducted with identical laser parameters. It is pertinent to point out that, employing the parameters shown in Fig. 1, the 4 mm thick materials could be drilled through in a single shot while the 8 mm thick sheets warranted multiple shots for complete drill through. For example, as shown later, the 8 mm thick IN718 material was drilled through in 15 shots while as many as 19 shots were required to drill the Ti–6Al–4V sheet. It is believed that the apparent reversal in the d_{entry} vs. Material-thickness trend noted in the present study is a result of the large difference in thickness that warrants vastly differing number of pulses. As opposed to single pulse drilling during which a significant amount of molten material is simultaneously ejected from the entry-side, results discussed subsequently in this paper have demonstrated that the volume of material removed per pulse is significantly less in case of percussion drilling of 8 mm thick materials and continuously decreases with progressive pulsing until complete drill through is achieved. This is on account of possible re-solidification of molten material on the side-walls during the process of ejecting the melt from a greater depth. The substantial reduction in volume of molten material outflow per shot also leads to much lesser erosion of the hole wall at the entry-side and is plausibly responsible for the lower entry diameter in case of laser drilling of 8 mm thick materials.

3.1.2. Evolution of hole and specific energy utilization

An elaborate study, involving generation of numerous samples by varying the number of pulses, was also carried out to understand the percussion drilling process better. This study was conducted on 8 mm thick IN718 and Ti–6Al–4V materials, which required a significant number of pulses for total drill through, as opposed to the 4 mm thick materials which could be drilled in a single pulse. The variation in drilled hole depth with number of pulses for both materials drilled under identical conditions is shown in Fig. 2. The results suggest that drilling was apparently more efficient in case of IN718 sheet (drilled with O_2) compared to Ti–6Al–4V sheet (drilled with N_2), as illustrated by the fact that the depth of hole achieved by a specific number of pulses is always found to be higher in IN718. In order to explain the above observation, it was deemed appropriate to ascertain theoretically the specific energy requirement for melting as well as vaporization of unit volume of IN718 and Ti–6Al–4V materials and compare these values with the experimentally calculated specific energy. The theoretical calculations of specific energy η (J m^{-3}) were made using the following expressions:

$$\eta_{\text{theoretical for melting}} = \rho_s[C_{ps}(T_m - T_i) + L_m] \tag{2}$$

$$\eta_{\text{theoretical for vaporization}} = [\rho_s\{C_{ps}(T_m - T_i) + L_m\} + \rho_l\{C_{pl}(T_v - T_m) + L_v\}] \tag{3}$$

where ρ_s is the density of the solid (kg m^{-3}), ρ_l the density of the liquid metal (kg m^{-3}), C_{ps} the specific heat capacity of the solid material (J kg^{-1} K^{-1}), C_{pl} the specific heat capacity of the liquid material (J kg^{-1} K^{-1}), T_m the melting temperature (K), T_v the vaporization temperature (K), T_i the initial temperature (K), L_m the latent heat of melting (J kg^{-1}) and L_v the latent heat of vaporization (J kg^{-1}). Using the thermo-physical properties of IN718 and Ti–6Al–4V materials as indicated in Table 2 [23], the above theoretically required specific energies were calculated for each material and these are also shown in Table 2. It is pertinent to mention that the thermo-physical properties, in fact, vary with temperature. While such dependence was ignored in the illustrative calculations, it may be noted that separate solid and liquid phase properties were considered for theoretical estimation of specific energy using Eq. (3).

The specific energy consumption was also experimentally determined as follows:

$$\eta_{\text{experimental}} = \text{no. of pulses} \times \text{energy per pulse (J)}/\text{volume of hole (m}^3\text{)} \tag{4}$$

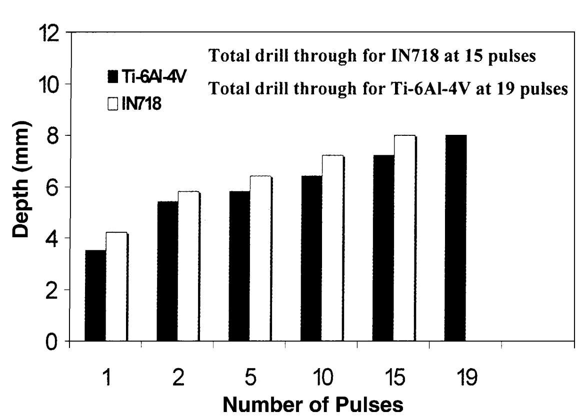

Fig. 2. Progressive variation in crater depth with number of pulses during laser drilling (pulse width: 0.7 ms, pulse energy: 7.5 J, pulse frequency: 9 Hz).

Table 2
Thermo-physical properties of IN718 and Ti–6Al–4V [23], and theoretical specific energy requirements for their drilling

	IN718	Ti–6Al–4V
ρ_s (kg m^{-3})	8.90×10^3	4.50×10^3
ρ_l (kg m^{-3})	7.90×10^3	4.11×10^3
T_m (K)	1728	1940
T_v (K)	3188	3558
T_i (K)	300	300
C_{ps} (J kg^{-1} K^{-1})	452	528
C_{pl} (J kg^{-1} K^{-1})	620	700
L_m (J kg^{-1})	2.92×10^5	3.65×10^5
L_v (J kg^{-1})	6.40×10^6	8.89×10^6
Theoretical specific energy for melting (J m^{-3})	0.83×10^{10}	0.55×10^{10}
Theoretical specific energy for vaporization (J m^{-3})	6.61×10^{10}	4.67×10^{10}

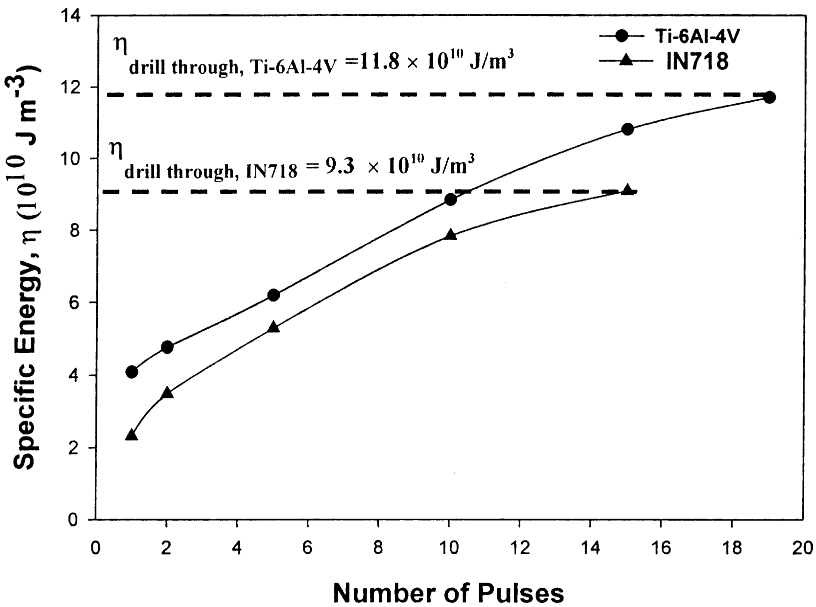

Fig. 3. Variation of specific energy for material removal with number of pulses (pulse width: 0.7 ms, pulse energy: 7.5 J, pulse frequency: 9 Hz).

The volume of the hole was calculated assuming the hole in each case to be conical. The variation in calculated specific energy consumption values with number of pulses is plotted in Fig. 3 and is extremely revealing. Fig. 3 clearly shows that the specific energy consumption progressively increases with number of pulses for any given set of laser processing parameters in case of both Ti–6Al–4V and IN718. This suggests that the material removal process, for a given material-thickness combination being drilled with a specific set of parameters, becomes increasingly inefficient as percussion drilling progresses. It is plausible that this is because of the need to expel molten material from a greater depth and the possible re-solidification of a larger portion of this melt as crater depth increases with progressive pulsing. The specific energy consumed for complete drill through was also calculated using Eq. (4) for both IN718 and Ti–6Al–4V and the values are shown in Fig. 3.

Based on the theoretically calculated and experimentally determined specific energy values, some interesting observations can be made. Foremost, it can be noted that the actual specific energy consumption is significantly higher than the theoretically predicted values. This can be attributed to the low absorptivity of the materials, in solid as well as in liquid phase, to the Nd:YAG laser beam. Although the precise absorptivity values of IN718 and Ti–6Al–4V are not known, the typical values for nickel and titanium metals are reported to lie in the range 15–33 and 26–43%, respectively, with the absorptivity value varying with temperature in the above range [24]. It is also pertinent to note that the experimentally determined specific energy consumption in case of IN718 is lower than that in case of Ti–6Al–4V, although the theoretically predicted energy requirements indicate otherwise. It should be borne in mind that the specific energy consumption calculated from Eq. (4) is based exclusively on the amount of energy provided by the laser beam without considering the contribution of the exothermic heat of reaction. As indicated earlier while explaining Fig. 1, the authors believe that the latter contribution can be significant during drilling of IN718 with O_2 gas assist and plays a crucial role with respect to energy requirements by substantially augmenting the energy provided by the laser beam. The large heat of formation (ΔH_f) of oxides like NiO and Cr_2O_3 that can form during the reaction of IN718 with oxygen [25] also supports this argument. Such contribution of exothermic energy is also widely proposed and well-accepted in case of laser cutting [26–28].

3.1.3. *Taper formation in laser drilled holes*

The hole diameter measurements have revealed that d_{entry} is invariably greater than d_{exit} throughout the present study. In this context it is relevant to mention that material removal during drilling occurs as a result of both vaporization and melting. The molten material is ejected out from the entry-side by the recoil pressure generated by material vaporization and, in the process, can erode the hole walls. Since the interaction between the melt and the hole walls is greatest at the entrance side and reduces with depth, d_{entry} values are typically larger as compared to d_{exit} and this is responsible for the presence of taper in laser drilled holes. The taper angle, as widely reported in laser drilling literature, is calculated using the expression given in Eq. (1) earlier and has been used as measure of hole quality in several laser drilling studies [5,6]. Therefore, the taper values were determined in case of all the laser drilled holes and the prominent trends observed are discussed in this section.

3.1.3.1. Taper variation with depth. Before embarking on a comprehensive study to assess the variation of taper angle

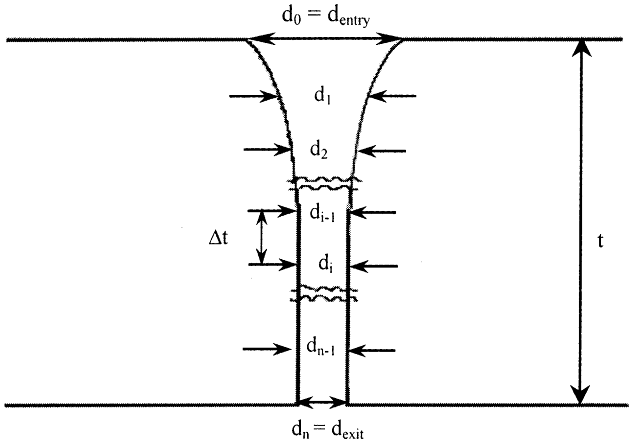

Fig. 4. Schematic representation of hole diameter measurements made in a laser drilled hole to ascertain taper variation with depth.

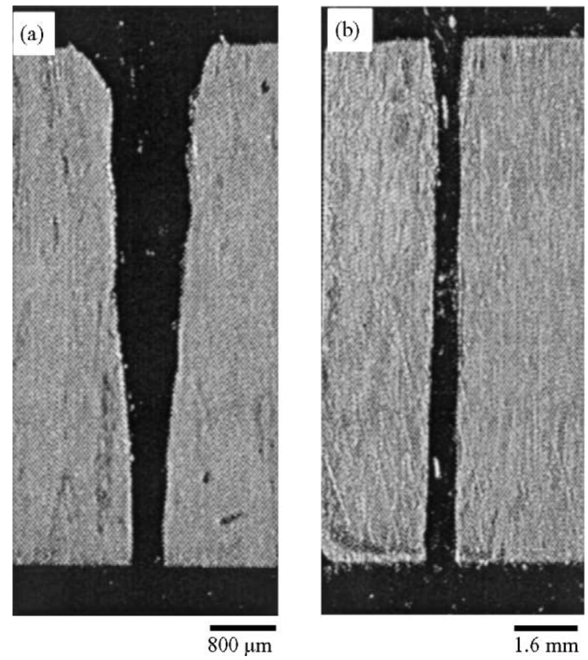

Fig. 6. Typical longitudinal cross-section of laser drilled hole in: (a) 4 mm; (b) 8 mm thick Ti–6Al–4V (pulse width: 0.7 ms, pulse energy: 15 J, pulse frequency: 4 Hz).

with process conditions, the general nature of the hole formed by the laser drilling process was thoroughly investigated. For this purpose, holes drilled in 4 and 8 mm thick IN718 and Ti–6Al–4V materials were sectioned and mounted as described in an earlier section and the diameter of the hole measured at fixed intervals along the depth as schematically illustrated in Fig. 4. The instantaneous taper at any given depth was calculated using an expression similar to Eq. (1) as:

$$\text{Taper}(\theta_i) = \tan^{-1}[(d_{i-1} - d_i)/(2\Delta t)] \quad (5)$$

where θ_i is the instantaneous taper angle at location i, d_i the diameter of the hole at depth location i, and d_{i-1} the diameter of the hole at a depth location Δt units above location i. In the present case, the hole diameter measurements were made 1 mm apart. The variation of instantaneous taper calculated using Eq. (5) as a function of depth is shown in Fig. 5 for all material-thickness combinations studied. The data clearly reveals that the taper is not uniform along the depth of the hole and varies particularly substantially near the entrance of the hole. To put the noted trend in the above figure in perspective, it may be pointed out that flattening of the taper angle vs. depth curve is suggestive of the hole attaining a conical shape, which is characterized by constant taper. If the curve flattens at a taper angle value close to zero, it is indicative of the hole attaining a near-cylindrical profile. For the process conditions adopted, Fig. 5 shows that, in case of the thinner 4 mm materials, the taper never attains a constant value while in case of the thicker 8 mm materials, the hole does approach near-cylindricity approximately after a 4 mm depth. The above trend is found to be true for both Ti–6Al–4V and IN718 materials. In order to illustrate this fact, optical micrographs of laser drilled Ti–6Al–4V samples

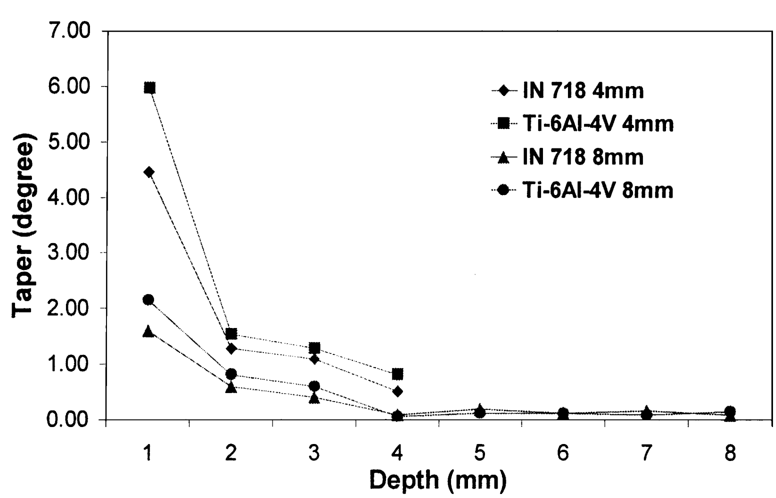

Fig. 5. Variation of taper with hole depth for different material-thickness combinations (pulse width: 0.7 ms, pulse energy: 15 J, pulse frequency: 4 Hz).

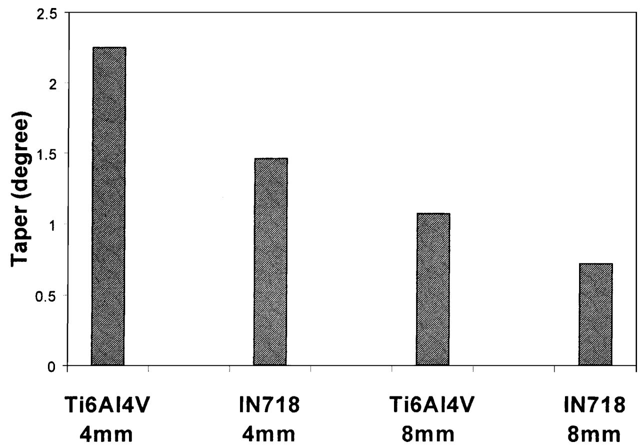

Fig. 7. Typical variation of hole taper with type of material and its thickness (pulse width: 0.7 ms, pulse energy: 15 J, pulse frequency: 9 Hz).

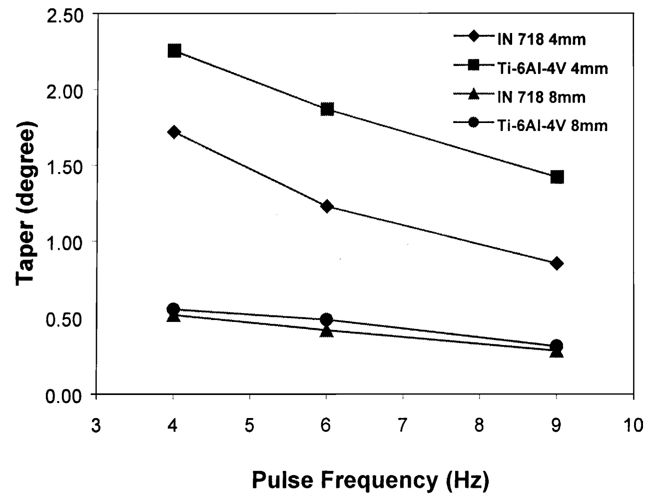

Fig. 8. Influence of pulse frequency on taper (pulse width: 0.7 ms, pulse energy: 15 J).

of 4 and 8 mm thickness are shown in Fig. 6. In any event, it is clear that the taper is not constant through the depth of the laser drilled hole. However, all subsequent results discussed in the paper present taper values determined as per Eq. (1) (which inherently assumes constant taper) for the sake of consistency with available literature on the subject.

3.1.3.2. Effect of material and thickness. Fig. 7 shows the taper values determined for various material-thickness combinations investigated in the present study under identical laser drilling conditions. As material-thickness increases, the amount of taper is seen to decrease, this being true for both the materials examined. A similar finding has also been reported in prior studies [5]. It has been pointed out by Yilbas [6] that liquid material ejection angle decreases in proportion to the diameter/depth ratio of the crater and, therefore, a large angle of liquid ejection is associated with relatively shallow holes leading to higher taper in thinner materials. Results in Fig. 7 also reveal that taper formation in Ti–6Al–4V is greater than that observed in an IN718 material of same thickness when both are drilled employing identical laser parameters. This is an indirect corroboration of the previously made suggestion that vaporization makes a relatively more significant contribution to material removal in case of laser drilling of IN718 with O_2, thereby suppressing hole wall erosion by molten material which is responsible for taper formation.

3.1.3.3. Effect of pulse frequency. The noted influence of the pulse frequency on taper angle in laser drilled holes is shown in Fig. 8 for a fixed pulse energy of 15 J and pulse width of 0.7 ms. The taper angle is seen to progressively reduce with increasing pulse frequency regardless of the material-thickness combination in question. It is also pertinent to point out that the pulse frequency was found to have a significant bearing on the number of pulses required to drill a hole. For example, at a frequency of 9 Hz, the Ti–6Al–4V material of thickness 8 mm was drilled through in 25 pulses whereas at 6 Hz nearly twice as many pulses were required. At a pulse frequency of 4 Hz, drilling was almost impractically slow. Such a trend is presumably a result of molten material being allowed to re-solidify due to the lower output power (which varies proportionally with pulse frequency) as well as the possibility of the greater time lapse between pulses during drilling at lower pulse frequencies.

3.1.3.4. Effect of pulse energy. During the present study, drilling trials were also performed to investigate the effect of varying the pulse energy from 7.5 to 15 J at a fixed pulse frequency of 9 Hz and pulse width of 0.7 ms. Fig. 9 depicts the variation in taper with pulse energy during laser drilling of 4 and 8 mm thick Ti–6Al–4V and IN718 materials. While the figure reflects the differences in taper angles with material and thickness, the influence of pulse energy

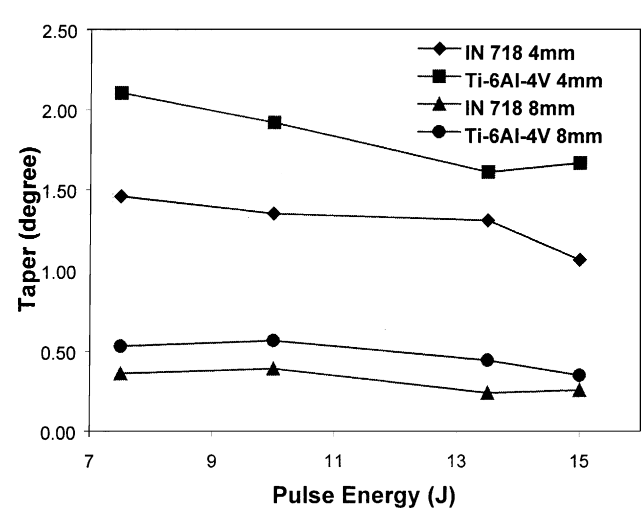

Fig. 9. Influence of pulse energy on taper (pulse width: 0.7 ms, pulse frequency: 9 Hz).

on taper angle for a given material-thickness combination is not seen to be very substantial. This is contrary to the significant increase in taper angle with pulse energy reported by Yilbas [6] in his laser drilling study on similar materials but of much lower thickness (0.25–1.5 mm), with a variation in pulse energy from 15 to 21 J. It is possible that the differing trends are a result of contrasting operating windows in respect of both material-thickness and pulse energy.

3.2. Metallurgical characteristics

All the laser drilled holes were also subjected to extensive metallurgical characterization. The extent and nature of the spatter formed around the hole periphery and the recast layer on the hole walls were studied along with the HAZ.

3.2.1. Formation of spatter

Spatter constitutes one of the inherent defects in laser drilling which results when the ejected material is not completely expelled but re-solidifies and adheres around the periphery of the hole [29]. During the present study, the extent of spatter formation, mainly observed at the entrance side of the hole, was found to be consistently more in case of thicker materials. This is presumably because expulsion of a greater amount of material is necessitated during drilling of thick sections as compared to thin ones. The IN718 and Ti–6Al–4V materials were also found to differ substantially in the extent of spatter formed and, as expected, its chemistry. Fig. 10 shows the entry-side hole morphology with spatter for 8 mm thick Ti–6Al–4V and IN718 sheet materials laser drilled under identical conditions. Two noteworthy features are immediately evident from the figure. First, it is abundantly clear that the extent of spatter formation is significantly greater in case of Ti–6Al–4V as compared to IN718. This provides additional proof for the previously made suggestion that material removal in case of IN718 is relatively more vaporization-contributed than in the case of Ti–6Al–4V. This leads to a smaller hole size, lower taper, less spatter and, as shown later, reduced recast layer formation. In addition, it is also plausible that the relatively lower density of the Ti–6Al–4V [24] also leads to the ejection of molten material over a wider area around the hole periphery.

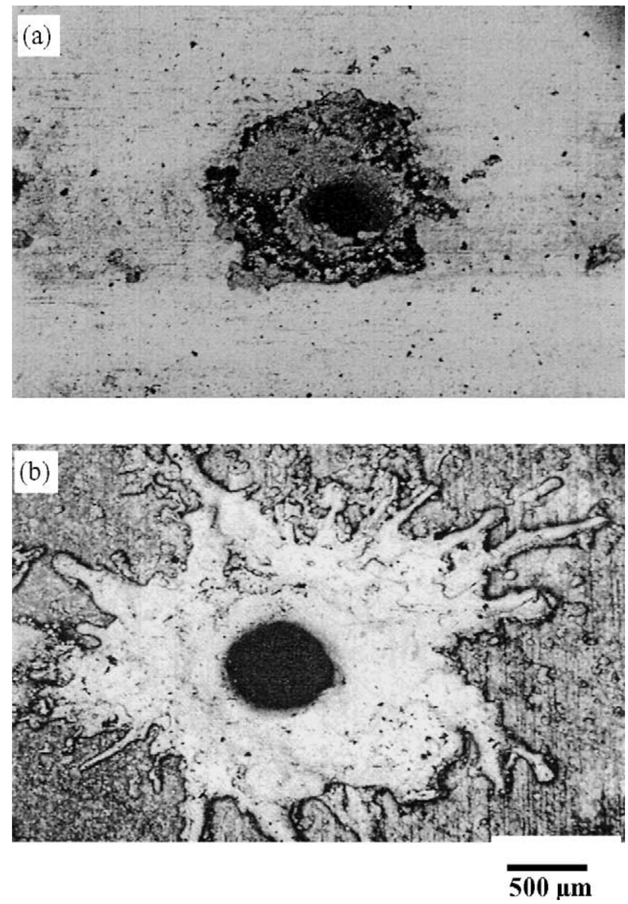

Fig. 10. Typical micrograph of spatter formation on the entry-side hole during laser drilling of 8 mm thick: (a) IN718; (b) Ti–6Al–4V (pulse width: 0.7 ms, pulse energy: 15 J, pulse frequency: 9 Hz).

Incidentally, a prior study [6] has also revealed that titanium yields huge amount of spatter around the hole periphery as compared to nickel. Apart from the obvious difference in the extent of spatter, the nature of the spatter observed in case of IN718 and Ti–6Al–4V materials is also found to be distinct. The dark color of the spatter in laser drilled IN718 samples is suggestive of oxide formation whereas the spatter in Ti–6Al–4V specimens is apparently constituted of bright re-solidified material.

Table 3
Relative wt.% of constituent elements in different regions of laser drilled IN718 and Ti–6Al–4V materials

Specimen	Region	Relative wt.% of elements							
		Ni	Fe	Cr	O	Ti	V	Al	N
Laser drilled IN718	Parent material	61.5	17.4	17.3	3.8	–	–	–	–
	Spatter	38.2	16.7	18.0	27.1	–	–	–	–
	Recast layer	45.4	15.9	16.0	22.7	–	–	–	–
	HAZ	56.1	21.6	18.9	3.4	–	–	–	–
Laser drilled Ti–6Al–4V	Parent material	–	–	–	–	86.7	2.9	5.7	4.7
	Spatter	–	–	–	–	78.8	2.7	4.4	14.1
	Recast layer	–	–	–	–	83.0	2.7	5.3	9.0
	HAZ	–	–	–	–	84.9	2.8	5.5	6.8

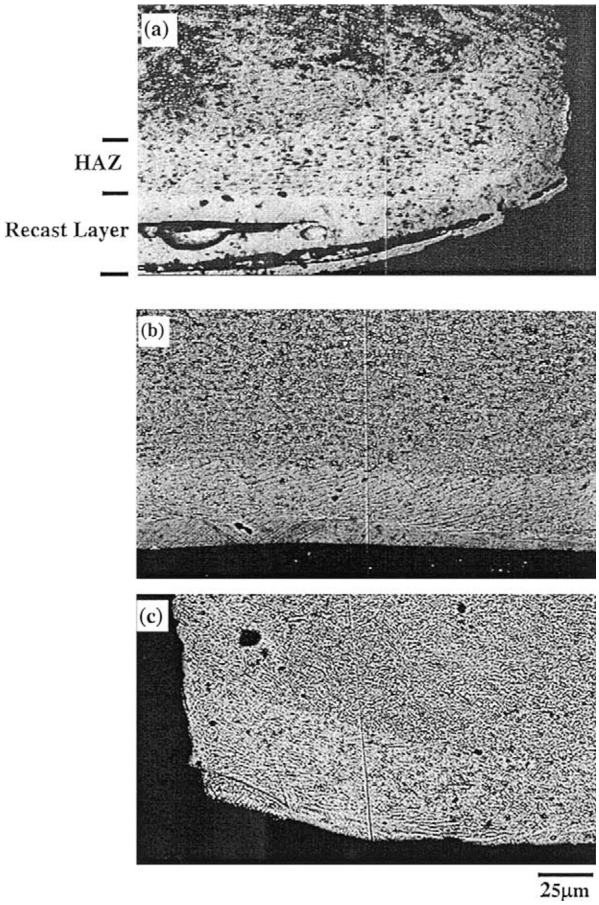

Fig. 11. Microstructures showing recast layer and HAZ in laser drilled 8 mm thick Ti–6Al–4V: (a) entry; (b) middle; (c) exit.

3.2.1.1. Elemental composition of spatter. Attempts were also made to ascertain the chemical composition of the spatter formed. Typical results obtained from SEM–EDS analysis on spatter resulting during laser drilling of 8 mm thick IN718 and Ti–6Al–4V materials are presented in Table 3. The data reveals that, in case of Ti–6Al–4V, which was processed using nitrogen as assist gas, some pick-up of nitrogen is evident. On the other hand, a substantial increase in oxygen content is noted in the spatter formed in case of IN718 material laser drilled with oxygen gas assist. Some nitride formation in the former case and significant oxide formation in the latter is plausible. It is also pertinent to point out that removal of spatter, which was carried out prior to hole diameter measurements as mentioned earlier, was much easier in case of IN718 than in case of Ti–6Al–4V indicating the oxide spatter in the former case to be only weakly adherent.

3.2.2. Recast layer and HAZ

3.2.2.1. Microstructure of recast layer and HAZ. Apart from spatter formation, the recast layer and the HAZ are two other metallurgical characteristics of interest in laser drilling and these two were also comprehensively investigated during the present study. Fig. 11 shows a typical low magnification microstructure of the recast layer and HAZ in laser drilled Ti–6Al–4V and also highlights the variation in recast layer and HAZ thickness with depth. This figure amply reveals defects such as cracks and voids particularly near the entry-side. However, as in the case of spatter, the recast layer in case of Ti–6Al–4V is clearly seen to be well adherent. On the other hand, the recast layer formed in the case of IN718 was found to be brittle and poorly adhered, and readily spalled during sample preparation precluding proper microstructural examination at low magnifications. Fig. 12 depicts the cross-section of recast layer and HAZ in case of 8 mm thick IN718. As in Fig. 11, the recast layer thickness is seen to vary substantially with location. However, the recast layer in case of IN718 is observed to be very non-uniform presumably because of spallation, and localized regions of recast layer detachment are also visible. A similar detachment of the recast layer in case of laser drilling of the nickel-base superalloy Nimonic 263 drilled with O_2 gas assist was also reported by Low et al. [30].

3.2.2.2. Variation of recast layer and HAZ thickness with depth. As evident from Figs. 11 and 12, the extent of recast layer formed was found to vary with depth, with the recast layer thickness being particularly significant at the entrance side of the hole as compared to the middle and exit-side of the hole for both IN718 and Ti–6Al–4V materials. The heat-affected zone, on the other hand, was found to be more or less uniform all along the thickness of the material. Greater recast layer formation near the entry-side of the hole is possibly the result of the fact that molten material ejection during percussion drilling takes place from this side. In view of the noted variation of recast layer thickness with depth, only the entry-side recast layer was considered in all subsequent discussions.

3.2.2.3. Effect of material and thickness on recast layer and HAZ. The extent of recast layer formation and HAZ was found to significantly depend upon the materials being drilled as well as their thickness, apart from the laser variables employed for drilling. Fig. 13 compares the recast layer and HAZ thickness obtained during drilling of various material-thickness combinations investigated in course of the present study under identical processing conditions. As seen from the figure, for same material-thicknesses processed under identical conditions, the recast layer and HAZ formed in the case of Ti–6Al–4V material were always thicker than those in holes laser drilled in IN718. As may be expected, the thickness of the recast layer and HAZ was found to increase with thickness of the material drilled. The results depicted in Fig. 13 also reveal that, depending on thickness of the material studied, the recast layer and HAZ thicknesses vary in the range 15–55 and 5–45 μm, respectively. These values are consistent with those reported in the literature [1].

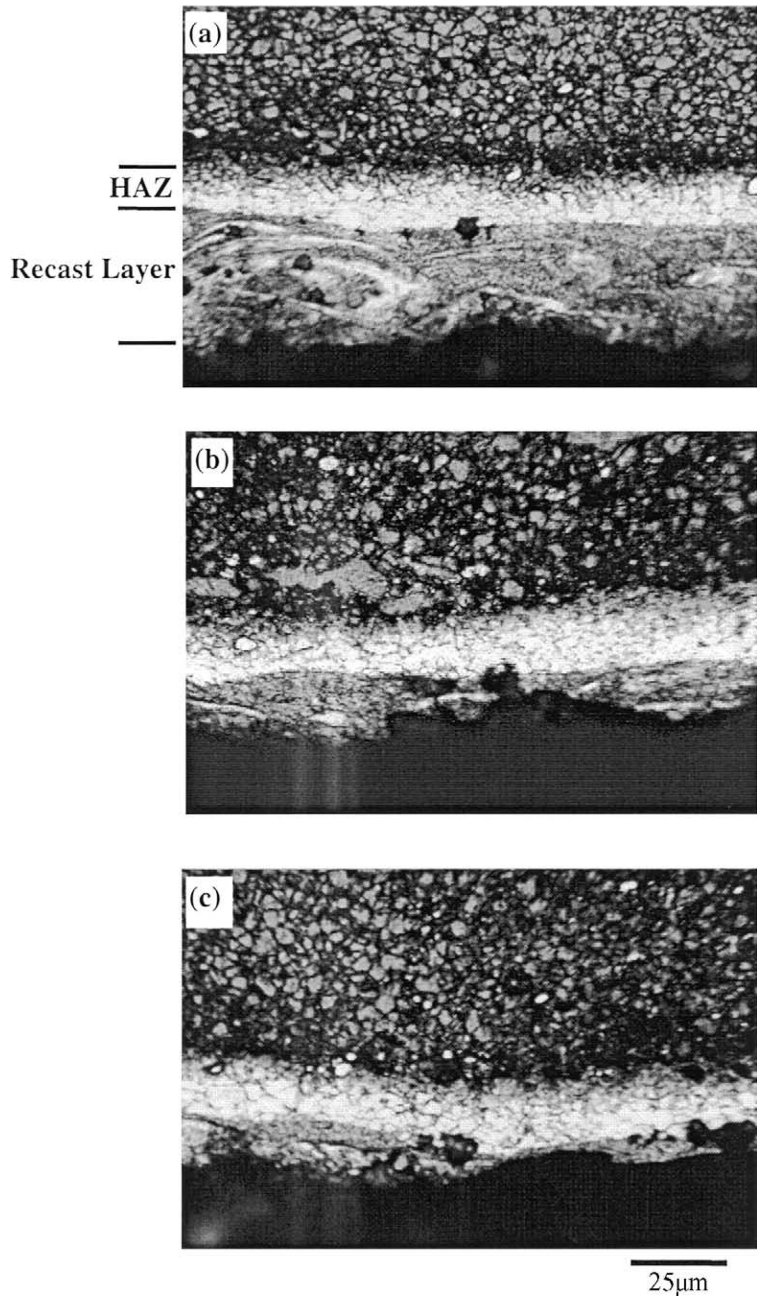

Fig. 12. Microstructures showing recast layer and HAZ in laser drilled 8 mm thick IN718: (a) entry; (b) middle; (c) exit.

3.2.2.4. Influence of process parameters on recast layer and HAZ. The variation in recast layer formation and HAZ with changes in pulse frequency and pulse energy was also investigated. Fig. 14 shows the effect of pulse frequency on recast layer thickness and HAZ during laser drilling of 8 mm thick IN718 and Ti–6Al–4V materials. While the recast layer thickness decreases with pulse frequency, the HAZ is found to remain nearly constant. It is summarized that the increased output power at higher pulse frequency enhances the contribution of vaporization to the material removal process, and, therefore, reduces the recast layer formation. The influence of pulse energy on recast layer and HAZ is depicted in Fig. 15. As the peak power is directly proportional to the pulse energy for a given pulse width, an increase in pulse energy is also likely to promote vaporization of the material during the drilling process. Consequently, the recast layer thickness is seen to decrease with pulse energy. The HAZ, however, is found to slightly increase when higher pulse energy is employed. Both these results are consistent with the results reported by Yeo et al. [5].

3.2.2.5. Elemental composition of recast layer and HAZ. As in case of the spatter formed, the recast layer and HAZ

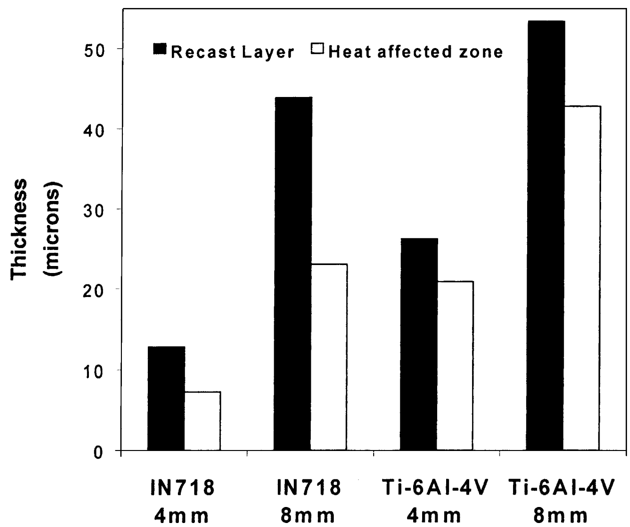

Fig. 13. Typical variation of recast layer and HAZ with type of material drilled and its thickness (pulse width: 0.7 ms, pulse energy: 15 J, pulse frequency: 9 Hz).

were also subjected to EDS investigation to ascertain elemental composition. The results are presented in Table 3 and reveal that the recast layer composition in the two materials almost follows the spatter composition, except that the pick-up of nitrogen and oxygen in case of Ti–6Al–4V and IN718 respectively, is somewhat suppressed compared to the spatter. Similarities in the recast layer and spatter compositions are only to be expected since both features result from re-solidification of the same molten material stream. On the other hand, analysis of the HAZ reveals a composition more or less similar to that of the parent material.

3.2.2.6. Hardness measurements in recast layer and HAZ. Microhardness measurements in the recast layer and HAZ were also made using an ultra-microhardness tester and the

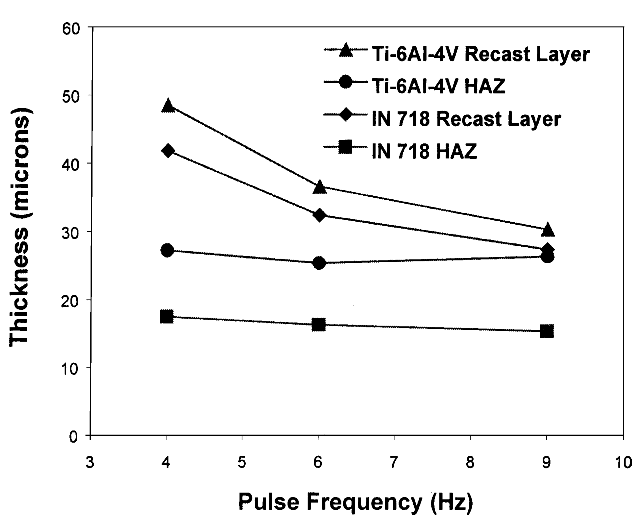

Fig. 14. Influence of pulse frequency on recast layer and HAZ thickness (pulse width: 0.7 ms, pulse energy: 15 J).

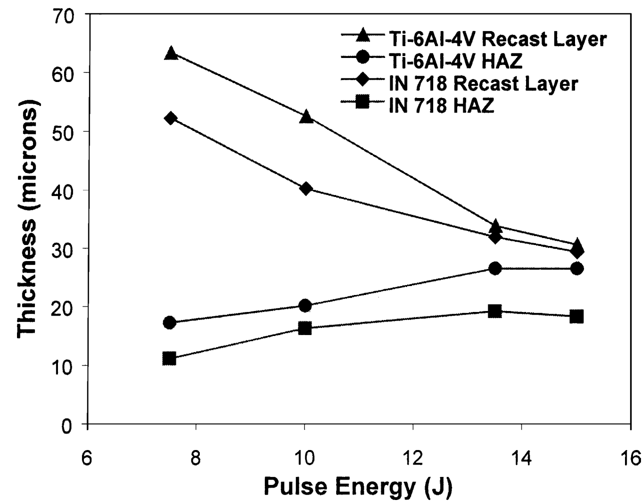

Fig. 15. Influence of pulse energy on recast layer and HAZ thickness (pulse width: 0.7 ms, pulse frequency: 9 Hz).

Table 4
Typical microhardness values in recast layer and HAZ

Material	Area	Microhardness (DHT115) range at 50 g load
IN718	Recast layer	680–710
	HAZ	350–380
	Parent material	350–380
Ti–6Al–4V	Recast layer	350–400
	HAZ	330–350
	Parent material	280–300

results are provided in Table 4. A total of four measurements were made in each region and the range of hardness values measured is indicated in the table. In case of IN718, the recast layer was found to have a substantially higher hardness than the HAZ. This can possibly be attributed to the formation of oxides such as NiO and Cr_2O_3, which have relatively higher hardness of 90–110 and 130–140 HRC, respectively [31]. The HAZ and the IN718 substrate are, however, seen to have similar hardness values and this is consistent with literature reports. In case of Ti–6Al–4V, the hardness values measured in the recast layer and HAZ are seen to be very similar and only marginally higher than the substrate hardness. This suggests that formation of nitrides such as TiN or AlN during laser drilling with N_2 gas assist is, if at all, extremely limited.

4. Conclusions

On the basis of the results ensuing from the present study dealing with pulsed Nd:YAG laser drilling of 4 and 8 mm thick IN718 and Ti–6A–l4V materials, the following conclusions can be drawn:

1. The hole quality, in terms of both geometrical features and metallurgical characteristics, is significantly influenced

by type of material and its thickness, as well as by key laser variables like pulse frequency and pulse energy.
2. In case of percussion drilling of thick sheets, the drilling process becomes increasingly inefficient as drilling progresses based on specific energy consumption for material removal.
3. The laser drilled holes are typically not perfectly conical and taper varies through the depth of the hole.
4. For a fixed set of laser variables, the taper in laser drilled holes decreases with material-thickness. However, the extent of spatter and recast formed, and to a lesser degree the HAZ, increase with thickness of material drilled.
5. The hole characteristics observed during O_2-assisted drilling of IN718 are substantially different from those noted in N_2-assisted drilling of Ti–6Al–4V. Results suggest that, for sheets of similar thickness drilled employing identical laser parameters, the IN718 material yields holes with a finer size, lower taper, less spatter and reduced recast layer as compared to Ti–6Al–4V.
6. All the above-mentioned hole features noted in case of IN718 can be explained by a more dominant role played by vaporization in the material removal process. These results also suggest that the exothermic oxidation reaction associated with O_2-assisted drilling of IN718 may be significantly augmenting the energy supplied by the laser beam.
7. Analyses of spatter and recast in case of IN718 and Ti–6Al–4V have also revealed significant presence of oxygen in the former case and some pick-up of nitrogen in the latter.
8. The pulse energy and the pulse frequency are both seen to effect hole quality. Higher values of pulse frequency are found to lead to lower taper and less recast formation. The trend with varying pulse energy is found to be similar, although the variations in the above hole features with change in pulse energy are somewhat more subdued.

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