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Cooling Ability-based Integrated Quality of Laser-drilled Holes

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ABSTRACT

Research aimed at improving the end-product quality in meeting the functional needs is imperative to sustain product development. Aerospace manufacturers are increasingly using percussion laser drilling for producing cooling holes in turbine components made of nickel base superalloys. Laser drilling of superalloys has been initiated at the Defence Metallurgical Research Laboratory, Hyderabad in the last decade keeping in view its uses in Kaveri Gas Turbine Engine programme. Considerable work has been carried out in this direction. Laser-drilled hole's quality issue has been addressed in the past considering separately the shape, precision, and functional characteristics of the laser-drilled holes. In the present investigation, a newer approach for defining hole quality has been reported which takes into account the above hole characteristics for computing cooling ability of the holes. This approach indicates that it is feasible to produce better integrated quality holes through laser drilling.

Keywords: Hole quality, air-cooled components, percussion laser drilling, nickel base superalloy, SUPERNI 263A, Nd:YAG laser

1. INTRODUCTION

Quality deals with enhancement of specific product characteristics to make the product more efficient. Therefore, even if the process used during product develop is the same, the quality characteristics are likely to be different for different products. In percussion laser drilling (PLD) process also, the quality characteristics are likely to be different for the holes produced for different purposes. For example, a hole used for lubrication purpose does not require tight tolerances compared to a hole intended for flow monitoring[1].

PLD is a multi-variable process and its output (the hole) also has multiple characteristics[2]. This complicates the determination of the quality of a laser-drilled hole. PLD has major application in aerospace industry for producing cooling holes in the gas turbine components made of nickel base superalloys, and therefore, is an important research area. The hole quality has been evaluated in terms of primary (shape (diameter, depth, taper, barrelling, recast layer, microcracking, inlet and exit angles)[2,3-13] and precision (repeatability))[13-17], and secondary (functional) characteristics of the holes[18-20] in the past. The presence of spatter in the vicinity of

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laser-rilled holes has also been considered in the quality criterion[21-24].

Shape and arrangement pattern of holes on their film cooling effectiveness have been studied. In general, slanted holes have been found to be more effective for film cooling[25-30]. Effectiveness of shaped (other than cylindrical) holes has also been studied. It has been found that shaped holes in the form of fanning out at entry and exit sides of the cooling fluid injection have improved film cooling effectiveness[31-34]. However, process of producing different types of holes has not been discussed in the above studies.

Above discussion on the past works reveals that various hole characteristics influence the hole quality and the same has been deliberated on the basis of specific hole characteristics. However, the hole quality based on functional characteristics, eg cooling of a component, has not been well investigated hitherto wrt different characteristics of a hole produced by PLD process. Hence, the present study is aimed at developing an approach to determine integrated quality of laser-drilled holes in quantifiable terms based on the cooling ability of the holes, which is likely to be dependent on their shape and precision characteristics, and computing integrated quality for the holes produced in a nickel base superalloy SUPERNI 263A at different PLD parameters.

2. EXPERIMENTAL PROCEDURE

A 400 W pulsed Nd:YAG laser integrated with a 5-axis CNC workstation was used to produce through holes in SUPERNI 263A sheets as per the criterion given by Pandey[35], *et al.* A 101.6 mm plano-convex quartz lens was used for laser beam focusing. The workpieces of the size 5 mm x 60 mm prepared from 0.5 mm and 1.5 mm thick sheets were kept at the optical focus of the lens normal to the laser axis. Peak power of the laser pulse was varied in the range 4-16 kW. Pulse duration and frequency were respectively 0.49 ms and 10 Hz. Commercially available high purity argon gas was used as the shielding gas at of 100 kPa pressure. Optimum stand-off distance[36] between the exit plane of gas delivery nozzle and the workpiece surface was 6.5 mm. Optical and scanning electron microscopes were used for hole characterisation.

3. DERIVING INTEGRATED QUALITY OF THE LASER-DRILLED HOLES

Functional characteristics (eg, cooling) of a hole or of an array of holes may be determined by the following methods:

- Estimation on the basis of hole characteristics
- Measurement during service or simulated service condition.

The first method may be used as a first step towards quantifying the hole quality which requires integration of the effects of various characteristics of a hole on the functional needs. Its index, denoting the integrated hole quality, may be used for comparing the holes produced at different combinations of PLD parameters, or by the other micro-hole drilling process (electro-discharge machining, electrochemical machining, etc).

The second method is very cumbersome and may not be feasible to apply during the component development stage.

It was proposed that shape characteristics of the laser-drilled holes be described by the geometrical parameters, namely, the diameters and the heights of zones for defining the quality of a laser-drilled hole on the above lines. The surface condition on the laser entry and exit sides of the workpiece in the vicinity of a hole may be discounted as the same can be improved by post-PLD processing or using anti-spatter coating. The precision aspect is to be evaluated wrt the geometrical characteristics of several holes. The precision characteristics may be computed on the basis of appropriate statistical measures, depending on the number of data points. The estimated standard deviation is the better measurement for smaller sample size (3-5 data points)[37].

Functional (cooling) characteristics of the holes are most likely influenced by the shape and precision characteristics of the holes. Figure 1 schematically shows dependency of the quality of the holes produced by PLD on the hole characteristics, which is used as a guide for quantification of the quality of holes produced in the present study by the PLD process.

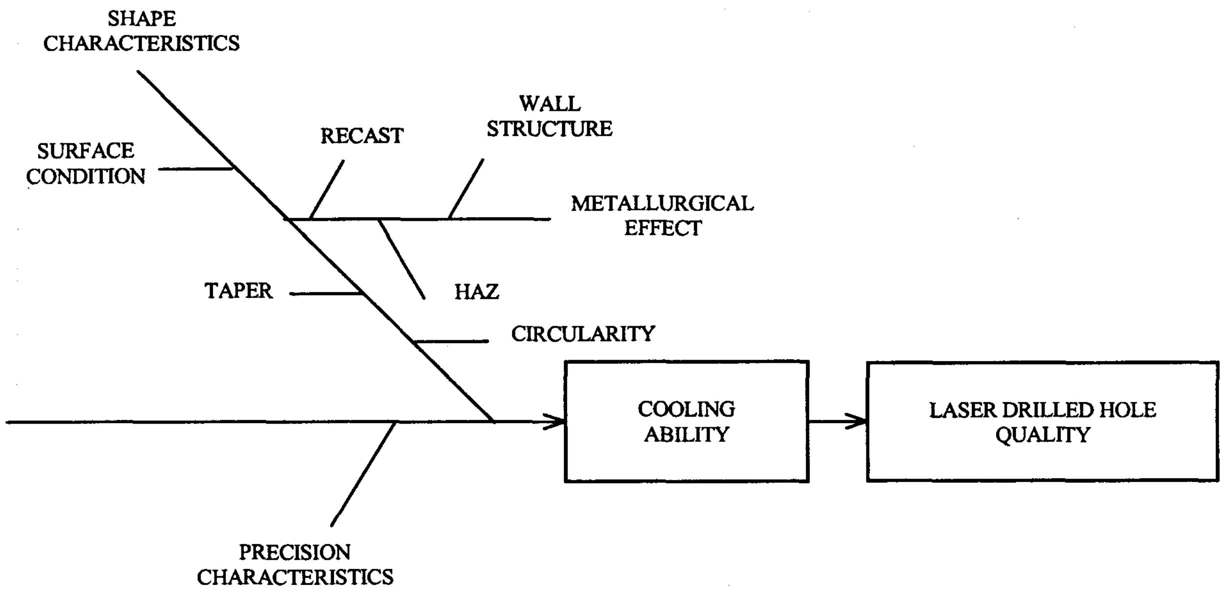


Figure 1. Percussion laser-drilled hole characteristics that affect its quality

The quality of a laser-drilled hole for the cooling function may be represented by its cooling characteristics and indexed in terms of cooling efficiency (η) of the hole. The cooling efficiency (η) can be estimated as below.

Suppose a fluid at temperature, T_0 is flowing through a hole in a component having uniform wall temperature, T (Fig. 2). If the heat transfer coefficient is h_f, the heat (q) extracted by the fluid while flowing through the hole is

$$q = h_f A_w (T - T_o) \tag{1}$$

where $T_0 < T$ and A_w is the surface area of the hole walls.

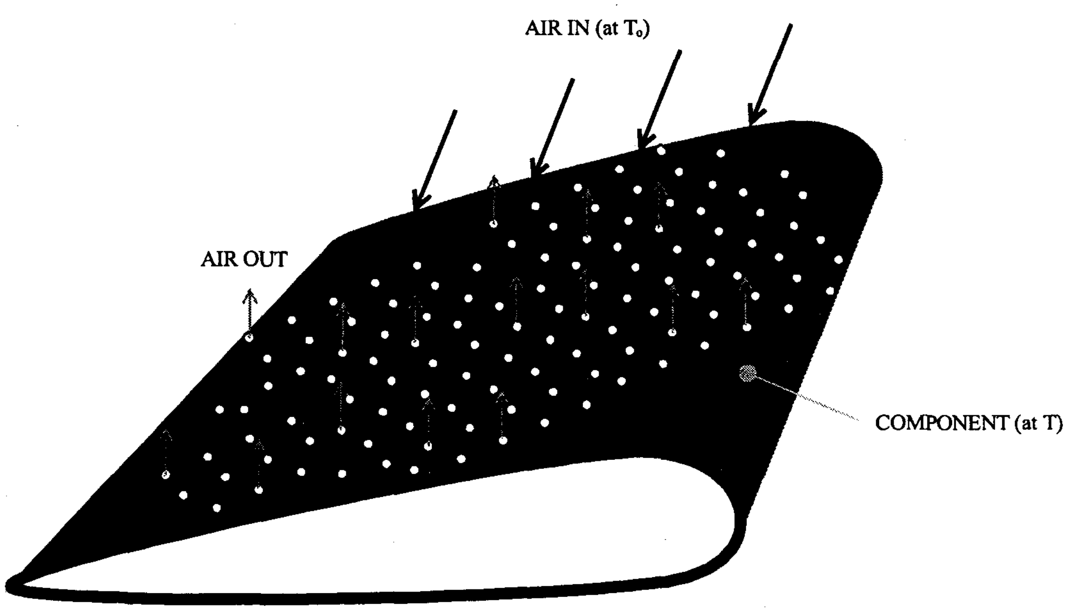


Figure 2. Fluid flow through cooling holes in a turbine component portion

In general, a typical through hole produced by PLD process has wall shape and structure as shown in Fig. 3(a), which may be represented by a schematic diagram[3] shown in Fig. 3(b). It can be seen that a hole has four identifiable diameters (d_1, d_2, d_3 and d_4). Its diameter d can be taken as the minimum among all the diameters

$$d = \text{Minimum } (d_1, d_2, d_3, d_4) \tag{2}$$

A laser-drilled hole appears somewhat like converging-diverging nozzle. Hence, the temperature of fluid passing through the throat (location of d) of the hole shall decrease and may be computed as follows:

The fluid enters the hole through the laser exit side of the workpiece and after diverging away from the throat, attains the temperature T', $T' < T_o$. T' may be expressed[38] by Eqn (3) as:

$$T' = \frac{T_o}{1 + \frac{k\text{-}1}{2} M_t^2} \tag{3}$$

where k is the ratio of specific heats and M_t is Mach number of the fluid at converging-diverging nozzle throat. It is assumed that the T' does not change as the fluid flows in diverging section of the hole.

The surface area of the hole walls [for computing q using Eqn (1)] may be determined based on the following assumptions:

- Walls of laser-drilled holes are axisymmetric
- Structural evolution is uniform in each structural zone
- Extent of each structural zone is axisymmetrically uniform
- A hole wall may be represented by straight-line segments in each structural zone.

Precision associated with the individual geometrical characteristics of the holes has to be taken into consideration by incorporating the concept of precision factor (p_f) while determining the cooling efficiency. The p_f may be derived from the value of the precision of the individual geometrical characteristics (estimated by standard deviation (SD)) calculated using Eqn (4) as

$$p_f = 1 - \text{SD} \tag{4}$$

It can be seen that the p_f assumes a value of 1 in the ideal condition where no variation exists in the values of a particular geometrical characteristics. A larger value of standard deviation implies lower precision, and subsequently results in the smaller value of p_f. The geometrical characteristics used for estimating the coolinf efficiency (η) have been multiplied with their respective p_f. The so modified characteristics are denoted in the following paragraphs by suffixing a prime (′) mark on the symbol of the individual geometrical characteristic.

A hole wall has three distinct structural zones (SZ) and three distinct geometrical zones (GZ) (Fig. 3). Figure 3(a) also shows high magnification photograph of all the three structural zones. The surface area of the each structural zone may be represented by that of a truncated cone.

For a typical hole section (Fig. 3), where $Sh1 < Gh1$, $Sh2 > Gh2$ and $Sh3 < Gh3$, the surface area of hole walls can be estimated as

$$A_w = S1 + S2 + S3 \tag{5}$$

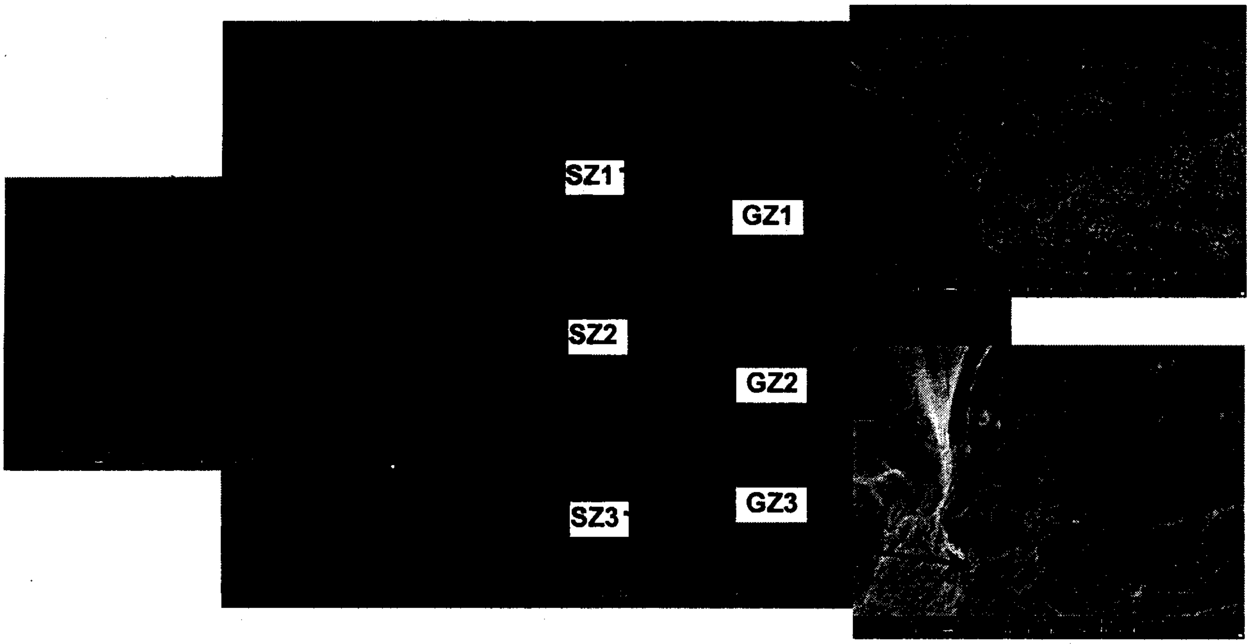
where $S1$, $S2$, and $S3$ are the respective areas of hole walls in SZ1, SZ2 and SZ3.

Revolution of line $L1$ (representing hole wall in SZ1, Fig. 3(b)) about the hole axis generates $S1$. $L1$ is represented by the following equation:

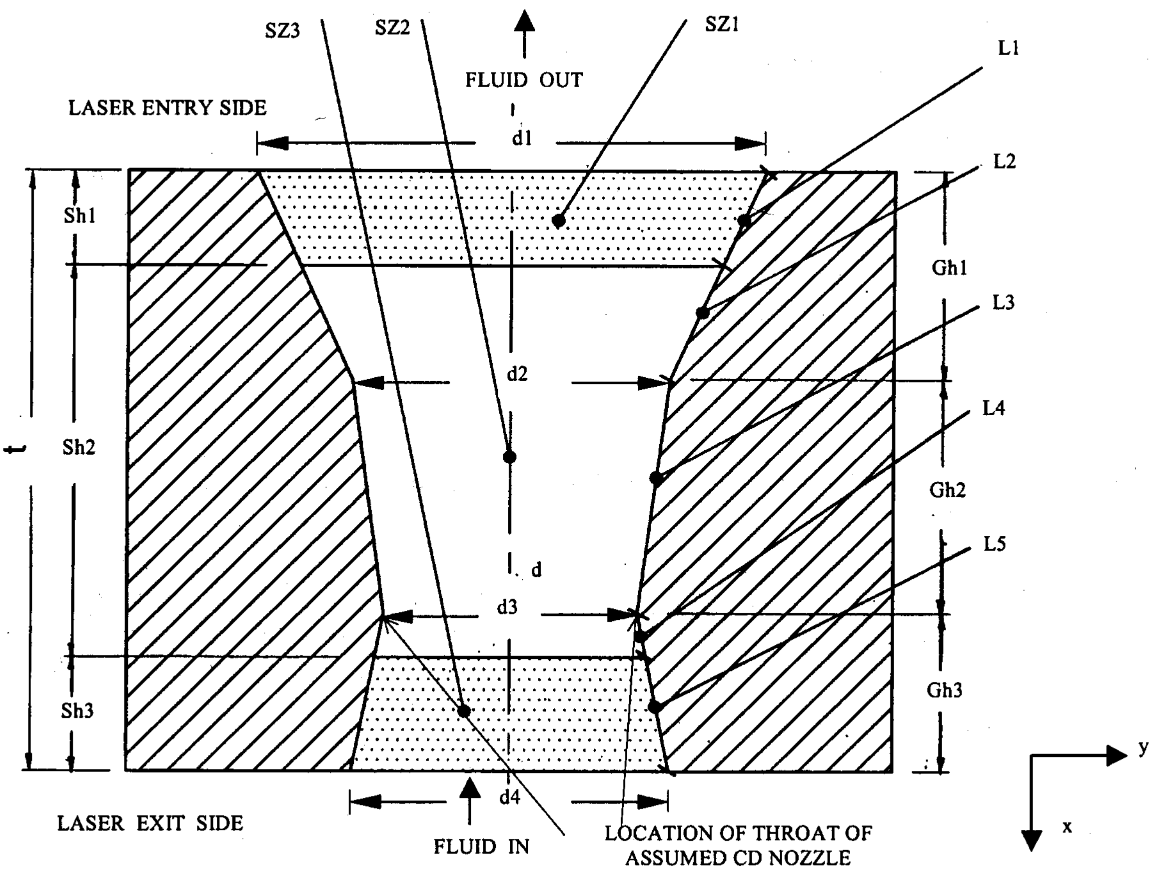
$$y = \frac{d1}{2} - t_1.x \tag{6}$$

where position of origin is assumed to be at the intersection of the hole axis (x-axis) and the plane containing the hole boundary represented by $d1$, $t1$ is the taper associated with GZ1, and x and y are coordinates. Hence,

$$S1 = \pi\, Sh1' \sqrt{1 + t_1'^2}\; (d1' - t'_1.Sh1') \tag{7}$$



(a)



(b)

Figure 3. A typical laser-drilled hole (a) transverse section (showing also wall structure at *SZ*1, *SZ*2, and *SZ*3), and (b) schematic diagram of a typical laser-drilled hole.

Revolving line segments $L2$, $L3$ and $L4$ around the hole axis generates $S2$, which is represented as

$$S2 = S2_2 + S2_3 + S2_4 \quad (8)$$

where subscripts denote the line numbers.

$L2$, $L3$, and $L4$ can be represented by the Eqns (6), (9) and (10) as

$$y = \frac{d2}{2} - t_2.x \quad (9)$$

$$y = \frac{d3}{2} - t_3.x \quad (10)$$

where position of the origin is assumed to the at the intersection of the hole axis (x-axis) and the planes containing hole boundaries represented by $d2$ and $d3$ respectively for line segments $L3$ and $L4$, and $t2$ and $t3$ are the respective tapers of $GZ2$ and $GZ3$. Surface areas $S2_2$, $S2_3$ and $S2_4$ are represented by the Eqns (11) to (13) as

$$S2_2 = \pi\sqrt{1+t_1'^2}\,[Gh1'(d1' - t'_1.Gh1') - Sh1'(d1' - t'_1.Sh1')] \quad (11)$$

$$S2_3 = \pi Gh2'.\sqrt{1+t_2'^2}\,(d2' - t'_2.Gh2') \quad (12)$$

$$S2_4 = \pi(Gh3' - Sh3').\sqrt{1+t_3'^2}\,(d3' + t'_3.Gh2') \quad (13)$$

The value of $S2$ may be computed by substituting Eqns (11) to (13) into Eqn (8).

Revolving line segment L5 [represented by Eqn (10)] around the hole axis generates $S3$ which is given by the following equation:

$$S3 = \pi Sh3'\sqrt{1+t_3'^2}\,[d3' + t'_3(2Gh3'\text{-}Sh3')] \quad (14)$$

Structures of $SZ1$ and $SZ3$ are quite rough in comparison to the structure of $SZ2$ as shown in Fig. 3. Assuming that the effective area of the rough surface is respectively l, m and n (depending on the degree of roughness) times its plain geometrical area. l, m and n are relative values and may be treated as roughness indices. Their values may be either computed as the ratio of surface roughness as

$$\text{Roughness index} = \frac{\text{Roughness of a } SZ}{\text{Minimum roughness of the } SZ\text{s}} \quad (15)$$

or may be assumed (in the absence of the surface roughness data) based on the visual examination of the respective SZs.

The heat q_l extracted by a fluid while flowing through a hole produced by the PLD process may be derived from the above equations as

$$q_l = h_f\{(T - T')[l.S1 + m.S2] + n.(T - T_o).S3\} \quad (16)$$

The heat q_s extracted by a fluid while flowing through a hole having diameter d [Eqn. (1)] and straight walls in the workpiece of the same material with thickness t is given by

$$q_s = h_f(T - T_o)[\pi d'.t'] \quad (17)$$

The cooling efficiency (η) of a laser-drilled hole may be represented as

$$\eta = \frac{q_l}{q_s} \quad (18)$$

3.1 Integrated Quality of Laser-drilled Holes

Various shape characteristics of the holes produced at different peak powers of laser pulses have been determined following the procedure*. The value of p_f for the respective geometrical parameters used for computing cooling efficiency (η) has been calculated using Eqn (4) and it has been multiplied with the particular geometrical parameter to obtain the modified parameter denoted by the prime mark suffixed on the individual geometrical parameter.

A comparative study of the hole wall structures indicated that the structure of $SZ1$ is smoother than that of $SZ3$ and the appearance of $SZ2$ is smoother than that of $SZ1$ and $SZ3$. The same is supported by typical structures of SZs shown in Fig. 3. As

* Pandey, N.D.; Shan, H.S. & Mohandas, T. Percussion laser-drilled holes: Characteristics and characterisation procedure. *Mat. Manuf. Proc.*, (in press and to appear in the first half of 2006).

Table 1. Roughness indices and integrated quality of holes

PP (kW)	Roughness indices for $t = 0.5$ mm			η for $t = 0.5$ mm	Roughness indices for $t = 1.5$ mm			η for $t = 1.5$ mm
	l	m	n		l	m	n	
4	1.25	1	2	2.36	1.5	1.25	2	1.88
8	1.5	1	2	2.33	1.5	1.25	2	1.86
12	1.5	1	2	2.63	1.5	1.25	2	1.63
16	1.5	1	2	2.96	1.5	1.00	2	1.56

the data of roughness of the *SZ*s are not available, the values of roughness indices [l, m and n, Eqn (15)] have been selected for a hole produced at the specific PLD parametric combination as between 1.0 and 2.0 on the basis of scanning electron microscope examination of the respective *SZ*. Table 1 shows the roughness indices for the studied peak powers. Further, the fluid is considered as an ideal gas and to compute the value of T', k = 1.4 and M_t = 0.4 have been selected. The values of T and T_0 has been selected respectively as 1600 K and 310 K. The T' has been computed as 300 K using Eqn (3).

The cooling efficiency (η) assumes the value of 1 for a straight-walled hole. The heat extracted by a fluid while flowing through such a hole is given by Eqn (17). The value of integrated quality in terms of η has been computed for the holes formed at all the studied values of peak power per pulse and listed in Table 1.

The improvement in the integrated quality (in terms of η) is in the range 56-196 per cent for the studied percussion laser-drilled holes in SUPERNI 263. A possible reason of this is conformance of the shape of all the through holes (encountered in the present study) to a particular shape as shown in Fig. 3. A critical examination of the hole shapes would indicate that the holes have fanned out on both the side of the workpiece. This shape of the hole has been reported to enhance film cooling effectiveness[32-35].

5. CONCLUSIONS

Percussion laser drilling improves efficiency of aero engine turbine components. Quality of the laser-drilled holes has been studied in the past considering their individual characteristics. Integrated quality concept in terms of cooling ability (considering shape and precision characteristics) of the holes produced in SUPERNI 263 has been developed. The quality of laser-drilled holes shows an improvement of 56-196 per cent compared to the straight-walled holes produced through other processes.

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