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ASSESSMENT OF SURFACE QUALITY IN EXTRUSION HONING PROCESS USING DIMENSIONAL ANALYSIS APPROACH

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ABSTRACT

It is critical to obtain the desired surface quality on machined parts' internal and external portions. The estimated level of surface texture can be induced on the outer regions using traditional finish machining processes such as grinding, honing, and so on. While the problem emerges when processing miniature core components such as micro bores and inlet/outlet valves. The EH approach overcomes this limitation of the conventional finishing method. It is a novel micromachining process that extrudes pressured flow of carrier media combined with abrasives into the confined passage to generate the desired level of surface texture. Due to the abrasion process, micromachining occurs by taking away negligible stock material. The present study focus on the impact of the number of passes at the specimen's entry and exit sides of the carrier media. The improvements in the surface finish (Ra) on both sides, i.e. entry and exit, are also evaluated. A dimensionless expression for Ra is also developed. The relation is implemented using Buckingham's π theorem, and the developed model is compared with experimental results. SEM analysis is made to portray surface texture produced by selected process parameters such as the number of passes, volume fraction and grit size of abrasive grains.

Keywords: *Extrusion Honing (EH), Surface finish (SF), Material removal (MR), Carrier media, Abrasives.*

1. Introduction

Abrasive flow finishing (AFF) is a deburring technique that develops compressive residual stresses while removing burrs and recasting white layers in the pre-machined component. This approach can process multiple passages in one or more components and tapered and stepped parts. This process is now known to be extrusion honing and, in some cases, abrasive flow machining (AFM). This technology covers a wide range of applications, including nozzles, manifolds, impellers, and prosthetic knee joints.

Finishing is due to the abrasion reaction of the pressurized polymeric media infused with SiC particles across the constrained path. Throughout this process, the abrasive dough flows across the substrate to be processed. The AFM technology is regulated by variables such as extruding pressure and flow velocity of media, distribution of SiC inside the media, and the number of carrier media passes.

This finishing approach guarantees the process geometric precision, applicability and effectiveness, which are crucial for mechanization. This technique accomplishes significant development in surface morphology with changing dimensions for the first pass itself. Finishing methods generally acquire 15 % of machining costs in the production cycle. In contrast, the marginal cost increases when the finishing value reduces below one micron.

Jain et al. 2000 investigated AFM, which improves the surface texture of unreachable areas, and the effect of parameters such as distribution and size of abrasive grains with media flow speed were performed on brass and aluminium. The investigated SF and MR responses agreed with the experimental values [1]. Extrusion honing (EH) is an excellent method for processing stiffer materials having complex profiles. From the available literature, it is witnessed that several researchers have tried this method for processing the class of materials.

Ravi Sankar et al. 2010 studied abrasion on Al/SiC MMCs by the R-AFF method. Ra is considerably improved when extruding pressure, rotational speed, cycles and % of lubricating oil (wt %)

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in carrier media are considered [2].Sudhakara et al. 2020 experimented with AFM on hollow cylindrical civilities. These specimens were made of Al 7075/SiC NMMCs produced by stir casting [3].

Mohammad Yunus et al. 2020 sought to anticipate the impact of factors like extruding pressure, grit size and the number of cycles on responses R_a and MR. Al/SiC particulate MMC with a high SiC % has been considered by constructing the Box Behnken design of RSM [4]. Several scholars repeatedly tried AFM processing on various materials that are softer or harder. For instance, Mejar Singh et al.2015 carried out studies on Al-6061[5], Amir et al.2018 and Ibrahim et al.2014 on stainless steel 304 [6] and low carbon steel [7].

Raju et al.2005 studied the material viewpoint of this deburring technology which has polished a wide range of materials. Furthermore, the authors have investigated roundness, bearing area and residual stresses of spheroidal graphite Fe [8]. Besides evaluating material removal [9-10] and producing the glazed surface texture in the given ferrous material [11-12].

Furthermore, the authors attempted the existing novel finishing process on other stiffer materials like Inconel-600[13], Inconel-718[14], Monel-400[15], Hastelloy C22[16], Titanium grade-2[17], Nitronic-60[18] and Nickel Alloy A-286[19] for assessing the final surface finish value with the influence of given process parameters for a different number of passes.

Murali Krishna et al. 2014 validated the use of this EH approach, revealing that irregularities of the EDM process, such as the recast layer, were removed. In comparison, evaluating the responses, this technique gives consistent results aligned with the experimental and theoretical results. Several scientists have attempted to model the EH process, which is still in the early stage. This is owing to the scarcity of information on the viscoelastic nature of media and the type of MR during micromachining [20]. Also, the performance of the micro-machining process was monitored by the acoustic emission technique [21]. Despite this, Jain et al. 1999-2004 achieved many results using finite element methodologies [22], stochastic simulation [23], neural networks [24], and genetic algorithm [25] techniques for evaluating the performance of the abrasive-based finishing method.

Jayasimha et al. 2021-2022 investigated the effect of VF of SiC on R_a, dynamic pressure and rate of strain on Inconel-625 in a one-way EH by employing a computational approach [26-27]. Meantime EH process is also modelled, and influential parameter among process parameters is determined [28]. To assess the capability of estimation, the experimental outcome is estimated using the ANN technique [29]. The research is strengthened by contrasting the final R_a for aluminium, copper, and titanium-Gr 2 alloys [30]. Moreover, the researcher emphasized developing a relation to determine the resulting surface finish [31].

The present study investigates surface finish R_a, surface texture and quantification of R_a by dimensionless modelling by considering passes, grit value and VF of abrasive in the flow media as process parameters.

2. Experimentation

The EH passes were executed in an in-house developed experimental arrangement. The various constants and parameters utilized in the study are listed in Table.1. Resulting EH surfaces were finally studied.

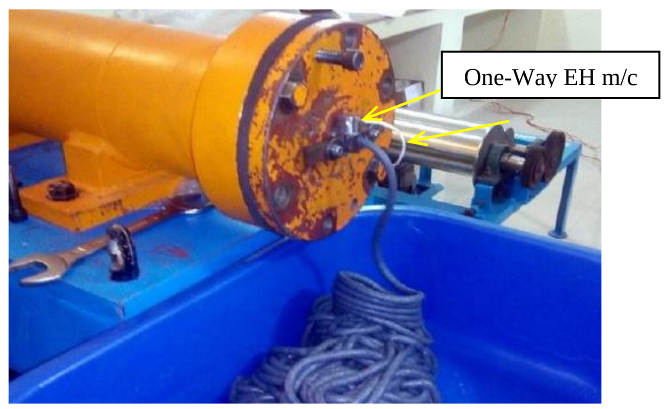

Fig. 1 Extrusion honing machine

The EH equipment is depicted in Fig.1, which incorporates a longitudinal cylinder carrying abrasive dough, flow regulating valve and a hydraulically controlled actuator. The current setup is irreversible, and the media flows only in one direction. The drum at the acute end is connected to a fixture to fit WP, and fastening is made to grip the specimen so that it can be attached and removed smoothly. Roughness characteristics were measured on the samples after EH experimental trials.

2.1 Carrier media

The carrier media in the EH process is a blended mix of silicone polymer and silicon carbide grains, as shown in Fig.2. The transporting media is prepared with known VF and the grit size of the abrasives. Media is proportionately blended and prepared using a house-developed media mixing machine, as shown in Fig.2 (d).

2.2 Material and specimens for EH

Inconel-625 is a nickel-based alloy widely used in elevated temperatures and corrosive environments because of its high resistance to heat and corrosion. The working temperature spans from cryogenic to 1350°C and is commonly employed in thermo-mechanical units. The influence of EH trials was performed on the Inconel alloy specimens having the geometry, span 13 mm, inner dia 7 mm, outer dia 20 mm and pre-drilled R_a of 2-3 μm.

Table 1 Extrusion honing process parameters

SL.No	Parameters	Value
1	Extruding pressure (bar)	60
2	Flow speed of media(m/min) F_s	0.3
3	Length of stroke (mm)	600
4	Number of passes N	15
5	Volume fraction (Abrasive %) C_a	35
6	Grit size of abrasive (microns) M_e	36
7	Temperature	Ambient
8	Dynamic viscosity of media (Pa. S)	20250
9	Density of media (Kg/m^3) ρ_m	1.13 ×10
10	Modulus of elasticity(Kg/m^3) E	2 ×10^{11}

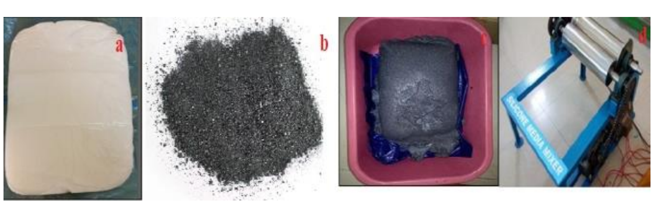

Fig. 2 a. Silicone b. SiC c. Media (Silicone + SiC) d. Media preparing machine

2.3 Evaluation

The resultant surface from the EH trials was wiped and decontaminated using compressed air and acetone. Consequently, the surfaces were subjected to SEM analysis and the surface finish was measured using Surfcom 130A, as illustrated in Fig.3.

Fig. 3 Surface roughness computing device (Surfcom 130A)

2.4 Influence of number of passes on surface roughness

The specimens were pre-machined by drilling, having a bore diameter of 7 mm. The EH passes were performed on these passage diameters using the carrier media, a mixture of SiC and silicone. The carrier media having an abrasive of 36 and VF of 35 % is used for experimentation.

The pilot tests were performed to identify effective process parameters for all factors and at different levels resulting in a better surface finish. These preliminary trials revealed that finishing values after the fifteenth pass exhibit higher roughness values. The EH passes were restricted to fifteen passes for all parameters.

The impact of parameters such as volume fraction and particle size of abrasive, number of passes and hole diameter for change in roughness characteristics are presented by plotting the corresponding graphs. The consequence of considered process parameters is evaluated regarding the influence of process factors on roughness parameters and percentage improvement in R_a. The extrusion-honed surface is analyzed under SEM under suitable magnification. The studies revealed that significant surface morphology improvement is observed in extrinsic features (surface parameters and texture).

As there are number of factors that decide the quality of surface while in the current study R_a is considered for evaluation. The surface roughness parameters were measured using Surfcom 130A at the carrier media's entry and exit sides. The surfaces of the specimen after each pass were measured regularly. The surface roughness values were noted initially and before and after each pass till the fifteenth pass of carrier media. Fig. 4 and 5 depicts changes in R_a, R_z, R_t and R_{pk} at both entry/exit region of carrier media in WP of bore dia 7 mm for the considered process parameters. From the plots, zero passes indicate the bore dia produced by drilling, while the consequent passes are the EH trials. It is evident from the same plots that drilled surface has high roughness values.

Figures 4 and 5 also illustrate the influence of 36 grit size of SiC in 35 %, volume fraction of SiC on surface roughness parameters on both entry/exit sides of specimen for 7 mm passage diameter. It is noticed that when contrasted to the entry side, the surface roughness parameters for all passage dia reduce at the exit side significantly, as shown in Figs. 4 and 5.

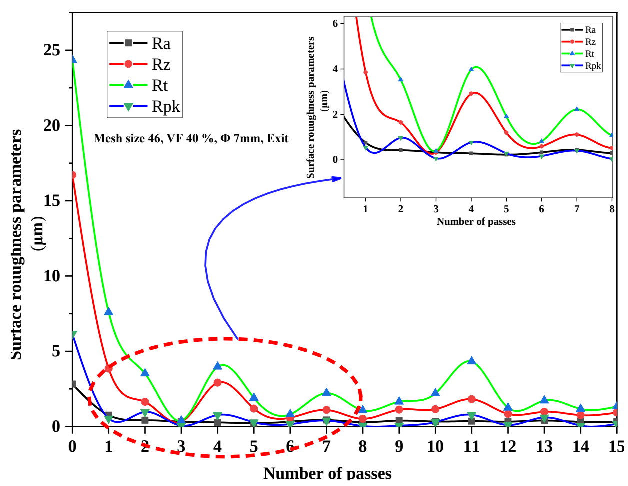

Fig. 4 Effect of the number of passes on R_a at the entry side

The initial surface induced due to the drilling process has a higher surface roughness value. The surface with enough peaks offers more resistance to the flow of carrier media; hence, most of the peaks get abraded at the early stage of extrusion honing passes. Consequently, it results in a high rate of reduction in surface values. Abrasives with larger mesh sizes mean fine abrasives, while smaller abrasives yield lower scratch levels, and the intensity of abrasion is also less. Irrespective of VF and mesh size of abrasives, R_a reduces at the first pass itself due to macro irregularity correction. It is presumed that it is because of the elimination of leading peak asperities, wear debris, and burrs across the passage length.

The slow progress of carrier media at entry creates a dead zone, resulting in light abrasion. As carrier media traverse across the passageway, the media relaxes the abrasives rapidly, makes enough contact at the exit side and yields a better surface finish.

It is concluded from Fig. 4 and 5 that significant surface finish values are achieved on both the entry and exit sides of WP. For WP of Φ 7 mm by 36 mesh size in 35 %, VF at the exit side of 0.01 µm and entry side of 0.0064 µm is achieved.

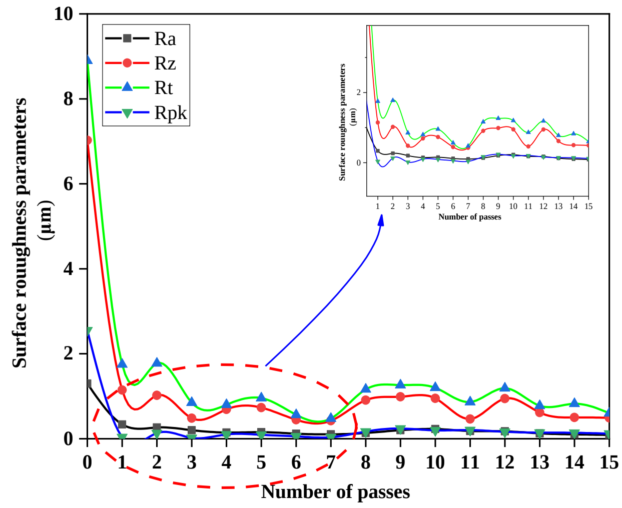

Fig. 5 Effect of the number of passes on R_a at the exit side

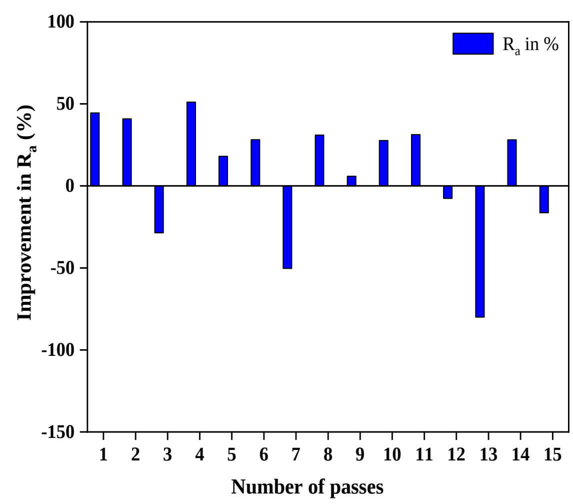

Fig. 6 Percentage change in R_a at the entry side of carrier media

Investigation on percentage improvement in R_a values

The resulting surface finish due to the EH effect is determined in terms of % improvement in R_a. Fig.6 and 7 show a % improvement in R_a at both the entry/exit side of WP. The attained outcome depicts that % improvement in R_a increments significantly for the first pass at both entry/exit sides of WP. It is due to the shearing of principal peak asperity and removal of remains and burrs on the initial EH surface. With a different number of passes, enhanced surface abnormalities are abraded. A considerable hike in percentage improvement in R_a signifies correction in micro irregularity.

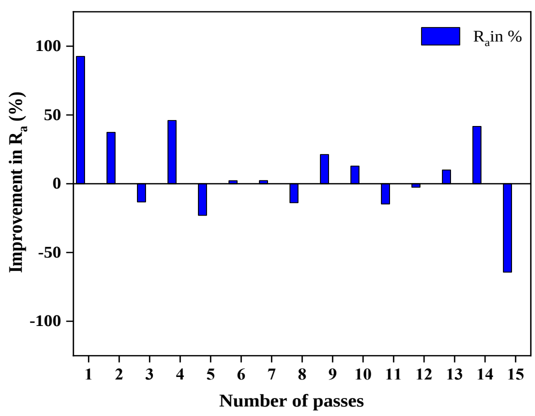

Fig.7 Percentage change in Ra at the exit side of carrier media

Further passes result in material spalling out and result in a surface drop. It is noticeably indicated by fluctuation in % improvement in R_a after the first to second passes and for subsequent passes. It is interpreted that this is due to scratching on material by abrasives on the super-finished surface, indicating correction in micro irregularities. It means the discontinuation of further EH passes, or if continued, it attains the phase of material spalling.

It is portrayed in the graphs that % improvement in R_a for all passes is high at the exit when compared to the exit. It is interpreted that it is because of the formation of a dead zone at entry, due to which carrier media become sluggish, resulting in dull abrasion at the entrance. While at the exit side, carrier media relaxes quickly because of better contact between abrasives and abrading surface. Consequently, there is a significant improvement in R_a value at the exit side. It is evident from the current study there is % an improvement of 43 % at entry and 95 % at the exit part.

3. Applying Buckingham's Π theorem

This method is applied to entire aggregate variables discovered in this study into a collection of dimensionless products. Algebraic equations are used to identify the required relation among discrete variables. To create a model using the π theorem, select recurring and non-repeating variables. The total number of repeated variables equals the number of fundamental dimensions, according to the Π theorem. Due to the criteria stated by π theorem, three variables are chosen as repeated variables [32].

The resulting response factor i.e. surface finish (R_a) on the specimen, relies on the following factors [31],

$$R_a = f(M_e, N, C_a, F_s, \rho_m, E) \quad (1)$$

Or

Equation (1) can also be expressed as below,

$$f(R_a, M_e, N, C_a, F_s, \rho_m, E) = 0 \quad (2)$$

$n - m = 7 - 3 = 4$ in this study,

Hence three π $-$ terms i.e $\pi_1, \pi_2, \pi_3, \pi_4$

Therefore $f(\pi_1, \pi_2, \pi_3, \pi_4) = 0$ (3)

According to the law of power indices on either side of the equation,

$$\pi_1 = M_e^a . F_s^b . \rho_m^c . R_a \quad (4)$$

$$\pi_2 = M_e^d . F_s^e . \rho_m^f . N \quad (5)$$

$$\pi_3 = M_e^g . F_s^h . \rho_m^i . C_a \quad (6)$$

$$\pi_4 = M_e^j . F_s^k . \rho_m^l . E \quad (7)$$

According to the law of dimensional homogeneity, each π term,

$$\pi_1 = M^0 L^0 T^0 = (L)^a . (LT^{-1})^b . (ML^{-3})^c . (L)$$

By comparing the power terms of M, L, and T on either side,

$$a = -1, \ b = 0, \ c = 0$$

By replacing a, b and c in π_1

$$\pi_1 = M_e^{-1} . F_s^0 . \rho_m^0 . R_a$$

$$\pi_1 = \frac{R_a}{M_e}$$

Similarly $\pi 2$, $\pi 3$ and $\pi 4$ are,

$$\pi_2 = N \qquad \pi_3 = \frac{C_a}{\rho m} \qquad \pi_4 = \frac{E}{\rho_m F_s^2}$$

Substituting values of π_1, π_2, π_3 and π_4 in equation (2)

$$f(\pi_1, \pi_2, \pi_3, \pi_4) = 0 \quad (8)$$

$$f\left(\frac{R_a}{M_e}, N, \frac{C_a}{\rho m}, \frac{E}{\rho_m F_s^2}\right) = 0 \quad (9)$$

$$\frac{R_a}{M_e} = k\left[N, \frac{C_a}{\rho m}, \frac{E}{\rho_m F_s^2}\right] \quad (10)$$

$$R_a = k\left[M_e \cdot N \cdot C_a \cdot \frac{E}{\rho_m^2 F_s^2}\right] \quad (11)$$

$$R_a = k\left[M_e^{\alpha} \times C_a^{\beta}\right] \quad (12)$$

4. Analysis of the dimensionless model

A dimensionless surface polish equation R_a was developed by taking the number of passes, flow velocity, media density, grit size, and VF of abrasives on a material while considering its modulus of elasticity. The model in this work links the response surface finish (R_a) with the process parameters by taking Young's modulus. The rationale of the developed equation is validated by carrying out associated experiments and determining the equation's constants and power indices using the least square method. The basic goal of creating a dimensionless equation is to build a relationship between process parameters and output responses.

Fig. 8 depicts the surface roughness achieved through experiments and projected by a dimensionless model for various passes with 0.35 volume fraction and mesh size 36. The plot clearly shows a progressive reduction in R_a as the number of passes enhances. The curve indicates an error between the experimental and projected outcomes. R_a reduces during early EH passes due to the reduction of peaks from the bored surface. After six passes, there is a slight improvement in Ra, but the surface texture deteriorates.

k is proportionality constants "α" and "β" are dimensionless model's power indices. The coefficient and power indices values must be established. As a result, a series of appropriate experimental trials are carried out. In the current study, regression analysis is employed to find out unknown values of proportionality constant and power terms based on the acquired results. The effect of pass number, grit size and volume fraction of abrasive on R_a is investigated in this study. While performing EH trials, the parameters ρ_m and F_s of carrier media are constants. The concluding equation with the value of proportionality constant and power terms is given by Equation (13).

$$R_a = 2.4056[M_e^{-1.5047} \times C_a^{-2.4552}] \times N \quad (13)$$

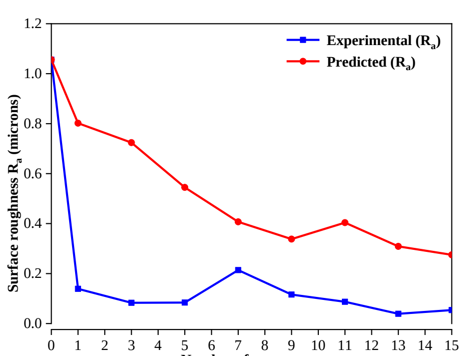

Fig. 8 Plot of experiment and predicted Ra for different EH trials

4. SEM analysis

Drilled and EH textures are investigated for SEM analysis to identify the effects of the extrusion honing technique on the surface texture generated. Fig.9 shows the typical SEM illustrations acquired before and after the EH. A machined mark caused by drilling is apparent and illustrated in Fig.9(a). The macrograph after five passes can be seen in Fig.9(b), which also notifies scrubbing of boring lay, the path of particle movement and abrasion dents. Additional trial of EH, as shown in Fig.9(c), the glazing pattern can produce a fairly consistent texture with a steady lay pattern. With additional EH trials, as seen in Fig.9(d), this material possesses a unique glazing structure and uniform texture after 15 passes.

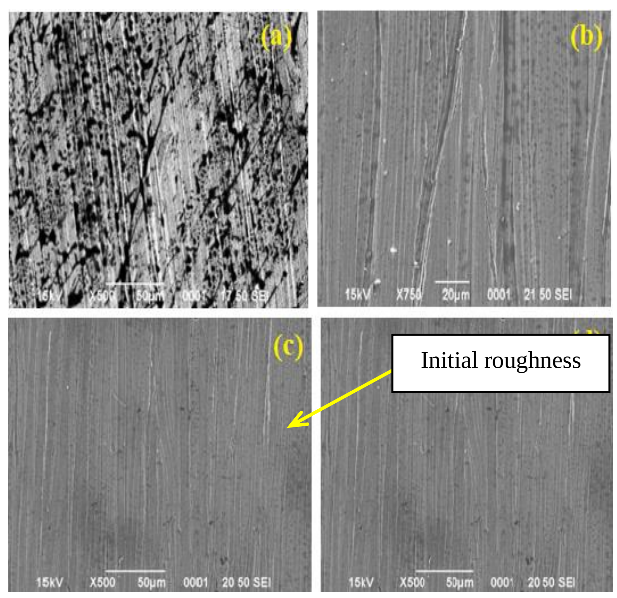

Fig. 9 SEM images of EH textures (a) As bored surface (b) after 5 passes (c) After 10 passes and (d) After 15 passes.

5. Conclusion

Challenging stiff material like Inconel-625 alloy is finish-machined using EH process by a select grade polymer. It is evident that the R_a reduces significantly at the early phase of EH process i.e at first and second pass itself. This is due to shearing of asperities and surface irregularities.

The EH process at pressure of 60 bar, abrasive grit size of 36 and 35 % VF, 15 number of passes and in 7 mm bore dia reveal appreciable results when interior surface of Inconel-625 alloy is extrusion honed.

EH trials are carried out for a given grit number and VF of abrasive for the given passage diameter on both entry/exit sides of carrier media. There is an extreme decline in surface finish. It happens from the second pass, after which there is a stable improvement in surface roughness up to the fifteenth pass with a diminishing surface with a further number of passes. After the first pass, surface roughness at both the entry and exit sides exhibit extensive abnormality in the surface texture generated by pre-honing. The sudden reduction in surface quality is because of the removal of principal peak asperities at early EH phases.

The exit side of the abrasive media exhibits a better surface finish than the entry side. It is due to the formation of a dead zone at entry while there is better contact of abrasive with the work surface at the exit side. SEM photographs of EH surfaces illustrate progress in surface texture quality, and a uniform lay pattern of surface texture can be visualized. Efforted to develop a dimensionless expression to evaluate R_a with the process parameters considered. It is witnessed that the predicted results achieved with the developed equation are in accord with the experimental results.

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