Overview on Burr Formation, Simulation and Experimental Investigation of Burr size — based on Taguchi Design of Experiments during Drilling of Alluminium 7075 Alloy

Reddy Sreenivasulu[1] and Chalamalasetti Srinivasa Rao[2]
[1]Department of Mechanical Engineering, R.V.R. and J.C. College of Engineering ,
Chowdavaram, Guntur, Andhra Pradesh, India
[2]Department of Mechanical Engineering, University College of Engineering,
Andhra University, Visakhapatnam, Andhra Pradesh, India
[1]rslu1431@gmail.com, [2]csr_auce@yahoo.co.in

Abstract — **The drilling of metals produces undesirable projections at the surfaces of holes called burrs, which are very costly to remove from the work piece. Burr formation in drilling operations causes products to be rejected or sent for deburring. Since deburring is a costly and non-value-added operation, the understanding and control of burr formation is a research topic with high relevance to industrial applications. This study focuses on the burrs formed in drilling of Al 7075 alloy at the exit side of the work piece. The results of this research show that the height and thickness of the burr that can be controlled by proper selection of drill bit that consists of suitable geometric parameters. In this experimental study, L27 orthogonal array of Taguchi design method, analysis of variance (ANOVA) was taken to find out the influence of process parameters on the response. Predicted values are finally checked for accuracy through a confirmation test. Confirmatory experiments were conducted for burr height and burr thickness, corresponding their optimal setting of process parameters to validate the used approach, obtained the values of 0.158 mm, 0.124 mm for burr height and burr thickness respectively.**

Keywords: Burr height, Burr thickness, Burr minimization, Taguchi method, ANOVA

I. INTRODUCTION

DRILLING is a machining process used to create or enlarge holes into or through a workpiece material. The process is performed with the use of a drill, which works by rotating at a fast speed while simultaneously being fed into the workpiece, removing incremental amounts of workpiece material. The drill itself, which performs the cutting action, has multiple cutting edges and flutes running along its length that allow the chips of workpiece material to be carried away. During the drilling process, burrs form on both the entry and exit surfaces as a result of plastic deformation of the workpiece material. Burrs are simply small amounts of attached material that protrude from the original entry and exit surfaces around the drilled hole. They are generally unwanted, and commonly need to be removed depending on the specific desired part geometry. If they are not removed, they can cause misalignment with adjacent parts. The burrs can also get detached from the surface and get trapped between mating surfaces leading to three-body abrasion and eventual failure of the assembly, among numerous other potential problems.

Literature on burr formation: The demands placed by designers on workpiece performance and functionality are increasing rapidly. Important aspects of manufacturing's contribution to the fulfillment of these demands are the conditions at the workpiece edges [1]. The presence of burrs on the edges of parts after machining, which may bring about a number of problems, makes deburring a necessary part of the production process.

The proper way of burr removal, the conditions of deburring, and the deburring cost depend on the part's features and the burr dimensions [2]. Not only deburring is a non-value-added process, but in many cases increasing burr formation is a key factor of cutting tool wear and leads to replacement of tools. Burrs do not have to be removed from a workpiece for functional reasons, there are still two dangers remaining. Firstly, burrs are often quite sharp and can lead to small finger injuries for assembly workers. Secondly, burrs which initially stick to a part can become loose during operation of a product and cause damage later on. In conventional drilling, burr formation can be changed by varying the drill's geometry [3]. Its formation is due to a plastic deformation on a ductile material.

This imperfection can be formed at the entrance as at the exit of a hole, although its appearance is more common on the last one. Presently, there are various international and national standards as well as proprietary standards for describing burrs and evaluating the quality of component edges. For thousands of years there was no word for a ‘‘burr’’ formed by machining, but Erasmus Darwin, grandfather of Charles Darwin, a naturalist and poet, appears to be the first person to mention ‘‘burr’’ in writing (1784). In the Oxford English Dictionary a burr is described as a rough ridge or edge left on metal or other substance after cutting, punching, etc.; *e.g.* the roughness produced on a copper-plate by the graver; the rough neck left on a bullet in casting; the ridge left on paper, etc., by puncture [1]

The ISO 13715 defines the edge of a workpiece as burred if it has an overhang greater than zero. Ko and Dornfeld [4] bases his work on this definition and defines a burr as an ‘‘undesirable projection of material formed as the result of plastic flow from a cutting or shearing operation’’. A comprehensive definition can be found in [5]. A burr is a body created on a workpiece surface during the manufacturing of a workpiece, which extends over the intended and actual workpiece surface and has a slight volume in comparison with the workpiece, undesired, but to some extent, unavoidable.

Kim *et al.* [6] categorize drilling burrs as uniform burr with or without a drill cap, crown burr or petal burr according to their shapes and formation mechanism. Two types of burrs, uniform burr (type I: small uniform burr, type II: large uniform burr) and crown burr, for stainless steel and three types of burrs, uniform burr (type I: small uniform burr, type II: large uniform burr), transient burr, and crown burr, for low alloyed steel were found as shown in (Fig. 1).

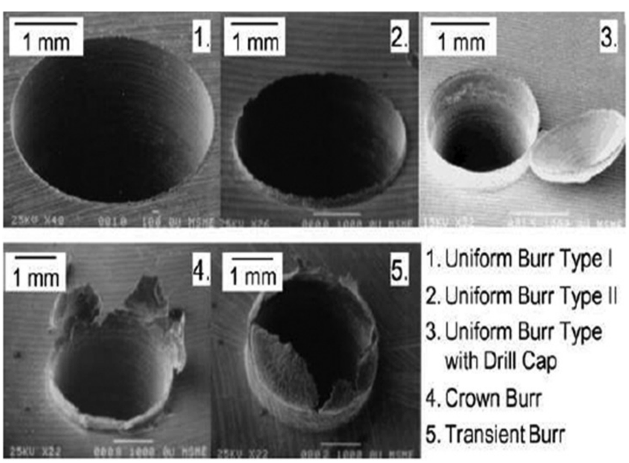


Figure 1. Typical drilling burr types according to CODEF.

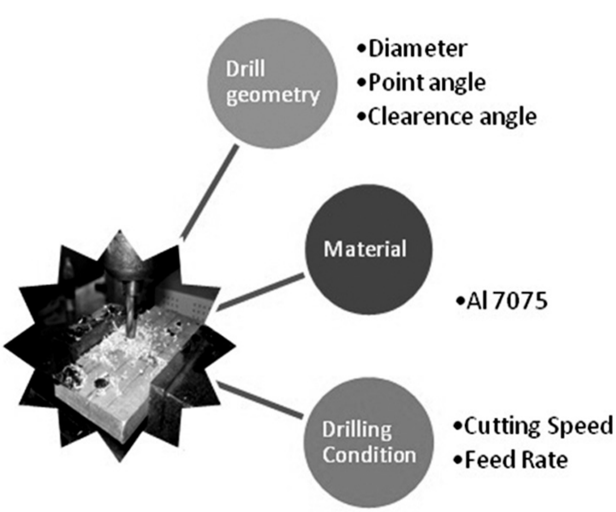


Figure 2. Factors governing burr formation**.**

Literature on parameters that influence burr formation: It is necessary to differentiate investigations which cover burr form and others that cover the topic of minimizing burrs. Gillespie and Blotter [7] already observe that burrs cannot be prevented by changes in feed, speed, or tool geometry alone. Still, the size of burrs produced can be minimized significantly by choosing appropriate machining parameters. To minimize and prevent burrs it is necessary to examine the entire cutting process. It is not sufficient to change only one process parameter as there are many influences between the parameters. Burr formation is affected by various parameters. Major effects are workpiece material, tool geometry, tool wear, tool path and machining parameters. In most cases a change of workpiece material is not possible. As to an improved tool path, this approach is also limited, as complex geometries would require burr optimized tool paths that prolong cycle time as negative effect.

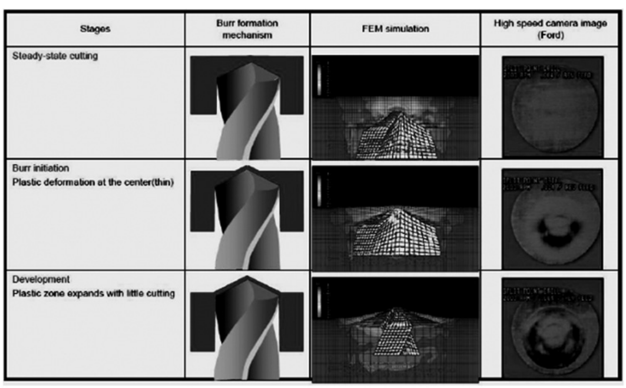
Link [8] point out that burr formation parameters cannot reliably be separated into direct and indirect factors due to the complex connections and relations between the numerous influencing variables (Figure 2). Wang and Zhang [9] investigate cutting burrs. The main factors of cutting direction burr formation are cutting parameters, the shape of the workpiece end, cutting tool geometry and workpiece material. The burr height in cutting direction is reduced with the increase in the depth of cut, feed, cutting edge angle and back rake angle. An increase of corner radius leads to increasing burr height.

Literature on simulation of burr formation: Due to the difficulties of analytical approach, extensive experiments have been done by several researchers. Gillespie [10] identified three stages of burr formation and Stein [11] classified burr geometry and identified burr influential factors for burr formation statistically. Kim [12] developed a control chart for prediction of burr type and size in drilling of stainless steel by split point twist drills. The further experiments to generate data on several aspects of hole quality will be done by Dechow [13]. However, understanding the drilling process mechanism by experiments has a limited insight. A simplified analytical model was proposed by Sofronas [14] and Lee [15] employed various feed control schemes to minimize burr size using the thrust force based on the Sofronas’ model.

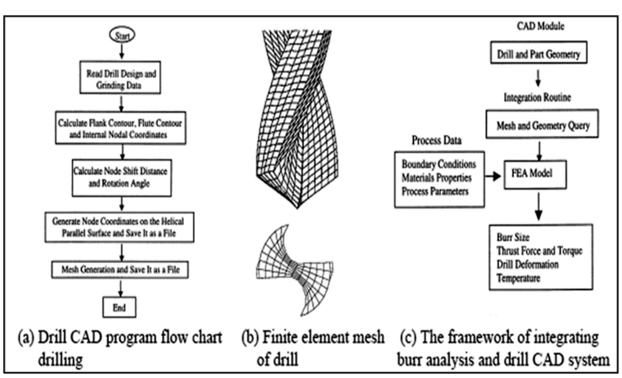
Both models cannot predict the burr geometry because a closed form analytical solution for drilling burr formation is extremely difficult to derive. A finite element model of drilling burr formation process, Fig 3(a), is developed by Guo [16]. The nonlinear thermoelastic- plastic model accounts for dynamic effects, strain hardening, strain rate, automatic mesh contact with friction, material ductile failure and temperature-mechanical coupling simultaneously.

Guo's finite element simulation gave an insightful description of drilling burr formation. He divided drilling formation mechanism into four stages: initiation, development, pivoting point and formation stages, Figure 3(a). Local fully plastic deformation initiates a burr at the edge of the workpiece with the initial plastic hinge formation within the workpiece. The development stage is characterized by smooth transition from cutting to plowing along drill lips due to the combination of shearing and bending. The pivoting point stage represents the formation of a stationary plastic hinge in the radial direction.

The burr thickness is largely determined by the distance between the pre-defined machined surface and the pivoting point. Finally, the burr formation stage represents the cap formation and removal, and the subsequent material roll-over process which continues to form the final burr. Cap formation



(a)



(b)

Figure 3*a.* Finite element simulation of burr formation in drilling machining (*b*) Automatic mesh generation for drill geometry and CAD/FEA integration.

and removal greatly affect burr size and shape. The burr height is determined by the positions of the pivoting point and the cap formation. The FEM simulation demonstrates the dominant roles of negative shearing and bending mechanisms in the drilling burr formation process.

Although the results of numerical simulation codes have been shown to be useful, such codes are not being used today in a manner that could have maximum potential impact on the drilling process due to the high cost of preparation for the process simulation by finite element analysis (FEA). With strong demand in industry for burrless hole making, it is desired to integrate FEA models with drill CAD to evaluate drill performance in the drilling process and fully utilize the benefits of this numerical tool in concurrent engineering. The complexity and various geometry parameters of a drill need a time consuming work to model and modify it. Hence, an integrated CAD/FEA system for drill design and drilling burr formation process (Fig.3b) was proposed by Guo [17].

After reviewed from references, finally found that burr formation is a complex mechanism to analyze and to prevent that, many researchers conduct their work related to burr minimization schemes towards basic machining processes such as turning, milling, grinding and drilling, but 100% not prevent to form it that is identified. So the objective of this study is to investigate the effects of the drilling parameters on burr size and is to determine the optimal drilling parameters using the taguchi design method.

II. EXPERIMENTAL INVESTIGATION

Material: The composition of Alluminium alloy 7075 consists of Aluminum (Al) 87.2 to 91.4 %, Zinc (Zn)5.1 to 6.1 %,Magnesium (Mg)2.1 to 2.9 %, Copper (Cu)1.2 to 2.0 %, Iron (Fe)0 to 0.5 %, Silicon (Si)0 to 0.4 %, Manganese (Mn)0 to 0.30 %, Chromium (Cr)0.18 to 0.28 %, Zirconium (Zr)0 to 0.25 %, Titanium (Ti)0 to 0.2 %, Residuals 0 to 0.15 %. In this study 300x50x10mm rectangular bar was used.

Schematic machining: In this study, the experiments were carried out on a CNC vertical machining center (KENT and ND Co. Ltd, Taiwan make) to perform different size of holes on Al7075 work piece by alter the point and clearance angles on standard HSS twist drill bits and maintain constant helix angle of 45 degrees. Furthermore the cutting speed (m/min), the feed rate (mm/rev) and drill diameter (mm) are varied in this experiment. The burr size (thickness and height) is measured by optical microscope (200 X magnification).

*Experimentation as per Taguchi Design Method: T*he orthogonal array forms the basis for the experimental analysis in the Taguchi method. The selection of orthogonal array is concerned with the total degree of freedom of process parameters. Total degree of freedom (DOF) associated with five parameters is equal to 10 (5X2).The degree of freedom for the orthogonal array should be greater than or at least equal to that of the process parameters. Thereby, a L27 orthogonal array having degree of freedom equal to (27-1) 26 has been considered, which is used to optimize the cutting parameters for burr height and burr thickness, using the S/N ratio and ANOVA for machining of Al 7075 alloy.

TABLE 1 -- MACHINING PARAMETERS AND THEIR LEVELS

LEVELS	FACTORS				
	Cutting Speed (rpm)	Feed Rate (mm/min)	Drill Diameter (mm)	Point Angle (Degrees)	Clearance Angle (Degrees)
	A	B	C	D	E
1	600	0.3	8	118	4
2	800	0.5	10	110	6
3	1000	0.6	12	100	8

TABLE 2 -- PLAN OF EXPERIMENTS BASED ON TAGUCHI ORTHOGONAL ARRAY AND OBSERVED RESPONSES

RUNS	TAGUCHI RESPONSE DESIGN TABLE							S/N Ratio
	Cutting Speed (rpm)	Feed Rate (mm/min)	Drill Diameter (mm)	Point Angle (deg)	Clearance Angle (deg)	Burr Height (mm)	Burr Thickness (mm)	
	A	B	C	D	E	R1	R2	
1	1	1	1	1	1	0.246	0.167	-1.6257
2	1	1	1	1	2	0.232	0.155	4.4302
3	1	1	1	1	3	0.226	0.150	-7.0661
4	1	2	2	2	1	0.265	0.197	3.7351
5	1	2	2	2	2	0.236	0.157	-4.5443
6	1	2	2	2	3	0.242	0.186	-5.4392
7	1	3	3	3	1	0.216	0.138	-6.1494
8	1	3	3	3	2	0.325	0.230	-4.8018
9	1	3	3	3	3	0.220	0.173	-1.2757
10	2	1	2	3	1	0.296	0.232	-4.4926
11	2	1	2	3	2	0.200	0.148	-1.0974
12	2	1	2	3	3	0.306	0.207	4.9104
13	2	2	3	1	1	0.206	0.145	-4.2678
14	2	2	3	1	2	0.178	0.140	-5.1281
15	2	2	3	1	3	0.165	0.153	2.1128
16	2	3	1	2	1	0.302	0.212	-5.0234
17	2	3	1	2	2	0.197	0.136	-1.8092
18	2	3	1	2	3	0.222	0.209	-6.8246
19	3	1	3	2	1	0.192	0.178	-3.2515
20	3	1	3	2	2	0.187	0.180	-3.3102
21	3	1	3	2	3	0.242	0.222	-4.6745
22	3	2	1	3	1	0.232	0.201	-3.8761
23	3	2	1	3	2	0.207	0.241	-3.6246
24	3	2	1	3	3	0.174	0.152	1.5275
25	3	3	2	1	1	0.164	0.141	-2.7174
26	3	3	2	1	2	0.201	0.158	-4.7837
27	3	3	2	1	3	0.219	0.187	-5.1285

TABLE 3 -- SIGNAL TO NOISE RATIOS (SMALLER IS BETTER)

Level	Cutting Speed (rpm) A	Feed Rate (Mm/Min) B	Drill Diameter (Mm) C	Point Angle (Deg) D	Clearance Angle (Deg) E
1	-2.52518	-1.79783	-2.66049	-2.10312	-2.44130
2	-2.41537	-2.18147	-2.17144	-3.45934	-2.74395
3	-3.31802	-4.27928	-3.42665	-2.69612	-3.07333
Delta	0.90265	2.48145	1.25522	1.35623	0.63203
Rank	4	1	3	2	5

TABLE 4 -- RESULTS OF ANOVA FOR BURR HEIGHT

Symbol	Parameters	DOF	SS	MS	F	
A	Cutting speed	2	0.00871	0.00435	36.25	significant
B	Feed rate	2	0.00292	0.00146	12.16	significant
C	Drill diameter	2	0.00218	0.00109	9.08	significant
D	Point angle	2	0.00684	0.00342	28.5	significant
E	Clearance angle	2	0.00140	0.00070	5.83	significant
Error		16	0.001926	0.00012		
Total		26	0.023976			

TABLE 5 -- RESULTS OF ANOVA FOR BURR THICKNESS

Symbol	Parameters	DOF	SS	MS	F	
A	Cutting speed	2	0.0066	0.0033	16.75	significant
B	Feed rate	2	0.0027	0.0013	6.598	significant
C	Drill diameter	2	0.0029	0.0015	7.614	significant
D	Point angle	2	0.00702	0.00351	17.766	significant
E	Clearance angle	2	0.0053	0.0027	13.705	significant
Error		16	0.00315	0.000197		
Total		26	0.02765			

TABLE 6 -- OPTIMAL VALUES OF INDIVIDUAL MACHINING CHARACTERISTICS

Machining Characteristics	Optimal combination of parameters	Significant parameters(at 95% confidence level)	Predicted optimum value	Experimental value
Burr height (R_1)	A1B1C2D1E3	A,B,C,D,E	0.158	0..164
Burr thickness (R_2)	A3B1C1D1E1	A,B,C,D,E	0.124	0.136

Though similar to design of experiment (DOE), the Taguchi design only conducts the balanced (orthogonal) experimental combinations, which makes the Taguchi design even more effective than a fractional factorial design. By Taguchi techniques, industries are able to greatly reduce product development cycle time for design and production, therefore reducing costs and increasing profit. Finally, confirmation test have been carried out to compare the predicted values with the experimental values confirm its effectiveness in the analysis of burr size. The machining parameters and their levels are given in Table1. Plan of experiments based on Taguchi orthogonal array and observed responses shown in Table 2.

II. RESULTS AND DISCUSSION

Analysis of the S/N Ratio: In the Taguchi method, the term ‘signal’ represents the desirable value (mean) for the output characteristic and the term ‘noise’ represents the undesirable value (Standard Deviation) for the output characteristic. S/N

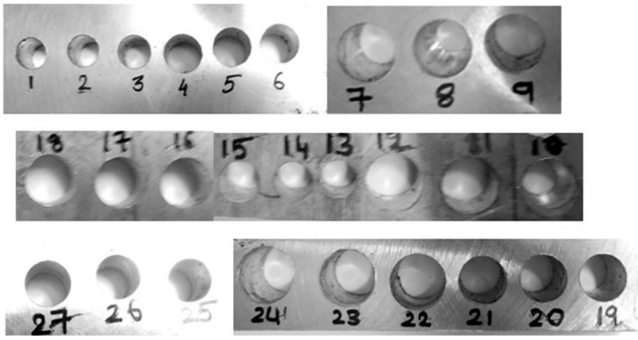


Figure 4. Images of drilled holes as per Taguchi design.

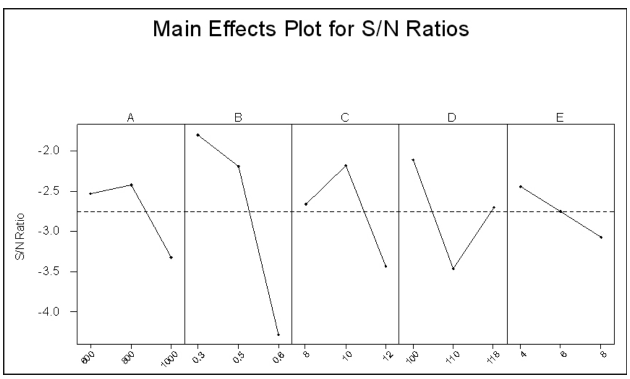


Figure 5. Response graph of S/N Ratio.

ratio used to measure the quality characteristic deviating from the desired value.

The S/N ratio (η) is defined as
$\eta = -10 \log (M.S.D)$,

where M.S.D is the mean square deviation for the output characteristic. Table 2 shows the experimental results for observed responses. The S/N ratio table for observed responses is shown in Table 3.

From main effects plot of S/N ratio for, the optimum parameters combination for burr height and burr thickness are A2B1C2D1E1 corresponding to the largest values of S/N ratio for all control parameters. From Table 3, it is observed that feed rate, point angle, drill diameter, cutting speed and clearance angle has the order of influence on burr size during drilling of Al 7075 alloy.

Results of ANOVA: The purpose of the analysis of variance (ANOVA) is to investigate which design parameters significantly affect the quality characteristic.
Table 4 shows the results of ANOVA for burr height, cutting speed, feed rate, drill diameter, point angle and clearance angle are the significant cutting parameters for affecting the burr height.

Table 5 shows the results of ANOVA for burr thickness, cutting speed, feed rate, drill diameter, point angle and clearance angle are the significant cutting parameters for affecting the burr thickness.

Significant, F_{table} at 95%confidence level is $F_{0.05, 2, 16} = 3.63$, $F_{exp} \geq F$ table

Significant, F_{table} at 95%confidence level is $F_{0.05, 2, 16} = 3.63$, $F_{exp} \geq F$ table

Confirmatory experiments were conducted for burr height and burr thickness, corresponding their optimal setting of process parameters to validate the used approach, obtained the values of 0.158mm, 0.128mm for burr height and burr thickness respectively. Predicted and experimental values of responses are depicted in table 6.

IV. CONCLUSION

The machining characteristics of Al 7075 alloy have been studied. The primary machining characteristics such as burr height and burr thickness were studied for drilling operation.

From S/N Ratio response table, feed rate, point angle, drill diameter, cutting speed and clearance angle has the order of influence on burr size during drilling of Al 7075 alloy.

From S/N Ratio response graph, the combination of parameters having the values of 800 rpm, 0.3 mm/min ,10mm.118 degrees and 4 degrees obtained for cutting speed, feed rate drill diameter, point angle and clearance angle respectively for optimizing burr size.

V. REFERENCES

[1]. J.C. Aurich. Burrs, ‘Analysis, Control and Removal’, *CIRP Annals - Manufacturing Technology,* Volume 58, pp. 519–542, 2009.

[2]. Andrey Toropov Sung-Lim Ko. “A Model of Burr Formation in the Feed Direction in Turning, *International Journal of Machine Tools & Manufacture,* Volume 46, pp. 1913–1920, 2006.

[3]. Sung-Lim Ko Jae-Eun Changa, Gyun-Eui Yang. ‘Burr Minimizing Scheme in Drilling’, *Journal of Materials Processing Technology*, Volume 140, pp. 237–242, 2003.

[4]. Ko SL, Dornfeld DA.. ‘A Study on Burr Formation Mechanism’, *Trans. ASME Journal of Engineering Materials and Technology,* Volume 113, No. 1, pp. 75–87, 1991.

[5]. Beier HM. *Handbuch Entgrattechnik: Wegweiser zur Gratminimierung und Gratbeseitigung fur Konstruktion und Fertigung.* Hanser Verlag (1999).

[6]. Kim J, Min S and Dornfeld D.,’Optimization and Control of Drilling Burr Formation of AISI 304L and AISI 4118 Based on Drilling Burr Control Charts’, *International Journal of Machine Tools & Manufacture, Volume* 41, No. 7, pp. 923–936, 2001.

[7]. Gillespie LK and Blotter PT, ‘The Formation and Properties of Machining Burrs’, *Trans. ASME Journal of Engineers for Industry* 98(1976):66–74.

[8]. Link R (1992) Gratbildung und Strategien zur Gratreduzierung, Dissertation, RWTH Aachen.

[9]. Wang GC, Zhang CY, 'Study on the Forming Mechanism of the Cutting- Direction Burr in Metal Cutting', *Key Engineering Materials* 259–260: pp.868–871, 2004.

[10]. Gillespie, L.K., "Burrs Produced by Drilling", Bendix Corporation, Unclassified Topical Report BDX-613- 1248, December 1975.

[11]. Stein, J.L., "Burr Formation in Precision Drilling of Stainless Steel", Ph.D. Dissertation, UC Berkeley, April 1989.

[12]. Kim, J., "Control Chart of Drilling Exit Burr in Stainless Steel", LMA Report, 1998.

[13]. Dechow, H., "Influence of Tool Geometry on Hole Quality when Drilling Ti-6Al-4V", LMA Report, 1998.

[14]. Sofronas, A., "The Formation and Control of Drilling Burrs", Ph.D. Dissertation, The University of Detroit, 1975.

[15]. Lee, G.B., "Digital Control for Burr minimization in Drilling", Ph.D. Dissertation, UC Berkeley, April 1989.

[16]. Guo, Y., "Finite Element Modeling of Drilling Burr Formation Process", M.E. Dissertation, UC Berkeley, 1997.

[17]. Guo, Y. and Dornfeld, D.A., "Integration of CAD of Drill with FEA of Drilling Burr Formation", *Trans. NAMRI/SME*, Volume 26, pp. 201-206, 1998.

Reddy Sreenivasulu is an Assistant Professor in the department of Mechanical Engineering, R.V.R & J.C College of Engineering (Autonomous) Guntur, AndhraPradesh, India. Rreceived B.Tech (Mechanical Engineering) degree from the Regional Engineering College, Warangal in the year 1997 and M.E degree from the University College of Engineering, Osmania University, Hyderabad in Automation & Robotics in the year 2003. He has 15 years of teaching experience. His area of research interest includes design of experiments, robotics, modeling and analysis of manufacturing