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# Study of cutting ability of centrifugal cast HSS cutting tool in optimized process parameters

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The purpose of the investigation is to propose an innovative method of single point cutting tool development adopting centrifugal casting operations. Scrapped cutting tools are melted, cast into cylindrical bars adopting centrifugal casting method, machined for developing single point cutting tools, and heat-treated for the conduct of cutting operations. Adopting Taguchi optimisation technique and considering the-smaller-the better approach, optimisation of cutting parameters viz, cutting velocity, depth of cut and feed rate for minimum surface roughness and cutting force are attempted during dry turning of mild steel (A36). Evaluation of the effect of cutting parameters on the output such as the surface roughness and the cutting force is done by using ANOVA software. The above mention studies are also repeated with the HSS cutting tool available in the market (HSS M2). The cutting ability of both tools on the basis of cutting parameters, as mentioned above is found to be at par. Also, analysis of wear characteristics yielded almost similar results. The study verifies the centrifugal casting method as a viable method for the development of single point cutting tools using scrapped tools.

**Keywords:** Cutting tool, Cutting parameters, Taguchi optimization technique, Surface roughness, Form stability

## 1 Introduction

The centrifugal force acting on the melt during its solidification in a rotating mould accounts for the production of a dense, compact casting sans any discontinuities in the concerned matrix during centrifugal casting. These are the castings with high metallurgical standards as directionality in solidification is ensured during solidification due to the rotation of the mould. Segregation of inclusions, grain refinement, and gradation of the microstructure resulting in a gradation of properties of the centrifugal casting are certain specific characteristics of centrifugal casting methods which can be taken advantage of for deciding the end-use of these products[1,2]. Luan *et al.*[3] have employed the centrifugal casting methods for the production of High speed steel (HSS) rolls that could result in eutectic grain refinement and its uniform distribution in the matrix for improving the wear resistance and thermal fatigue properties, the most sought after characteristic requirements of any machine tool.

Single point cutting tools, in general, are developed from high speed steel adopting conventional methods of tool making which include casting, forging, machining, and heat-treatment techniques. These can also be made by adopting spray forming[4] and powder metallurgy[5,6] techniques. In-situ laser melt injection technology for the improvement of tool surface property[7,8], chemical/physical vapour deposition technique for deposition of different coating materials[9,10] on the tool surface, and cryogenic treatment techniques for improving the tool characteristics[11] are also practiced for improving the performance of single point cutting tools.

The outcomes of cutting operations carried out by single point cutting tools, viz. surface roughness obtained and the cutting force requirements can be assessed with different combinations of cutting parameters which include the cutting velocity, the depth of cut, and the feed rate. Several combinations of these parameters are possible increasing the number of experiments to be conducted to analyse the contribution of each of the cutting parameters towards the process outcomes, namely the cutting force requirements and the surface roughness of the workpiece. These high numbers of experiments make the process of study time taking and cumbersome. In order to answer these difficulties, therefore, several mathematical models based on neural network techniques or statistical regression methods are made available for the selection of the appropriate combinations of cutting parameters[12-15]. However,

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these models are complex and need considerable depth of knowledge for implementation. Therefore, the Taguchi method of experimental optimisation[16-18] which is efficient and offers an easy method for optimising process parameters with the basic aim of reducing the number of experiments for any specific investigation can be adopted for this purpose. Several investigators[19-22] have adopted this technique for evaluating tool performance by optimising the various cutting parameters. The analysis of variance (ANOVA) has been adopted by these investigators to evaluate the contribution of each of the cutting parameters towards the outcomes of the single point cutting operations.

Keeping the above in mind, the present investigation is adopted centrifugal casting methods for development of the single point cutting tool from scrapped tools. This enabled the investigators to do away with the stringent methods of control of chemical composition of the melt assuming minimal melting losses and also the costly forging operations for tool compaction. Taguchi experimental optimisation technique is adopted on the basis of 'the-smaller-the better' approach for deciding the minimum number of combination of cutting parameters. Evaluation of the contribution of each cutting parameters towards the surface roughness and the cutting force requirements are accomplished by ANOVA analysis. The experiments are also repeated for the conventional HSS (HSS M2) single point cutting tool available in the market. The cutting parameters and tool-geometry remained the same as with the developed tool. A comparative study of the performance of the conventional HSS tool and the centrifugal cast single point cutting tool is made under identical operating conditions.

## 2 Experiment for development of HSSCT from scrap cutting tools and machining on workpiece

### 2.1 Details of the experiment for production of HSSCT blank

The photograph of the vertical centrifugal casting setup fabricated in the central workshop of our Institute (Institute of Technical Education and Research, SOA deemed to be University) is shown in Fig. 1. Split mould as shown in Fig. 1 made of mild steel which consists of two parts assembled by clamping arrangement for easy removal of the cast product. The top part of the mould was properly supported by the ball bearing as shown in Fig. 1 to maintain the axis of mould vertical with the base plane in order to avoid vibration and any deflection during rotation. The bottom part of the mould was connected to the pulley and motor arrangement. The rotational speed of the motor was controlled by controlling the input voltage through a variac.

Scraps pertaining to broken and worn out HSS cutting tools of single point cutting tools and multi-point cutting tools were collected as the raw material. Most of these broken tools contained broken HSS lathe tools, milling cutters, reamers, broaches, etc. Melting was done using an induction furnace. After sufficient superheat of molten metal in the furnace, the molten metal was poured into the mould rotated at 350 rpm to get the required centrifugal force during solidification. After solidification, the centrifugal cast product was then cut and machined into one of the standard square shank size piece of 12mm×12mm×120mm for the development of the cutting tool of the required tool geometry. Prior to tool angle grinding, the cutting tools were heat treated. For the heat treatment, the cutting tools were heated in a raising hearth furnace at 1200°C for 2 hours. Then, the tools were subjected to sudden water quenching. The composition of centrifugal cast HSSCT blank and its hardness is given in Table 1.


Fig. 1 — Photograph of centrifugal casting setup.

Table 1 — Material composition and hardness of centrifugal cast cutting tool.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Alloys | Fe | C | Si | Mn | P | S | Cr | Mo | Ni |
| Composition% | Balance | 0.3 | 0.0393 | 0.12 | 0.0636 | 0.0296 | 1.44 | 1.7 | 0.230 |
| Alloys | Al | Co | Cu | Ti | V | W | Nb | Sn | |
| Composition % | 0.0101 | 0.307 | 0.102 | 0.0288 | 0.277 | 2.94 | 0.0020 | 0.001 | |
| Hardness | 54HRC | | | | | | | | |

Hardness was measured using Rockwell hardness tester. However, a hardness drop was noticed in the case of the developed tool (54 HRC). This could be because of the composition of scrap materials. As compositional adjustment was eliminated during the process, no additional alloy was added externally. Also, carbon loss during melting reduced the overall carbon percentage and decreased the hardness. However, a reduction in hardness didn't significantly hamper the cutting performance.

The traditional method of HSS single point cutting tool production includes gravity casting or die casting of blank followed by the complex heat treatment process, forging process, and machining out of the tool pieces from the forged blank. The conventional gravity or die casting includes an expensive process of compositional adjustment which requires the addition of expensive alloys, skilled workforces, etc. However, the current method of manufacturing HSS cutting tools excluded the cumbersome process of compositional adjustment and costly forging method step. The current method of manufacturing cutting tools included the casting of HSS blank using centrifugal casting technique followed by machining out of standard cutting tool shank from the blank and a heat-treatment process. Centrifugal casting is known to produce a dense, compact, defect-free casting with directional properties[1], thus, eliminating the forging step required. Also, the addition of alloying element cost was eliminated. Eliminating the forging process reduces the overall tool manufacturing cost as the forging process needed the installation of forging setup, forging machinery, skilled workforces, and forging time. Thus, considering the above, the current method can be a way to minimize the overall manufacturing cost of HSS single point cutting tools.

#### 2.2 Development of single point cutting tool

The geometry of the cutting tool with respect to angles plays a very important role in the machining process. By proper selection of tool angles, tool life is enhanced and a large number of components can be produced in a given time with retaining form accuracy and surface roughness. Improper selection of tool angles leads to an increase in surface roughness, cutting force, vibration, temperature, and tool wear. Considering these constraints on tool angles, tool angles were selected for HSS tool material and most common mild steel work material on turning process. These angles were specified as per American Standard Association System (ASAS) in Fig. 2. As specified angles in Fig. 2, the centrifugal cast HSS square piece was ground using a tool and cutter grinding machine.

#### 2.3 Details of the experimental workpiece

In the present experimental investigation, the most commonly used material mild steel (A36) was considered as workpiece material to study the performance of developed centrifugal cast HSSCT on simple machining process as turning. In this study, a mild steel workpiece of 40mm diameter, 200 mm long was used as workpiece material for finish turning operation. Table 2 contains the composition and hardness of mild steel (A36) workpiece. Mild steel is one of the most used and cheaper materials in day to day life and in the manufacturing industry.

#### 2.4 Experimental procedure

The performance of developed centrifugal cast HSSCT was verified by very simple operation on the workpiece that is finished turning to keep on view surface roughness and force required for machining on workpiece comparing conventional HSSCT (HSS M2). Generally, to get lower surface roughness, feed rate and depth of cut should be low with high cutting velocity in finish turning operation. In this regard, tool life will be decreased as per Taylor's tool

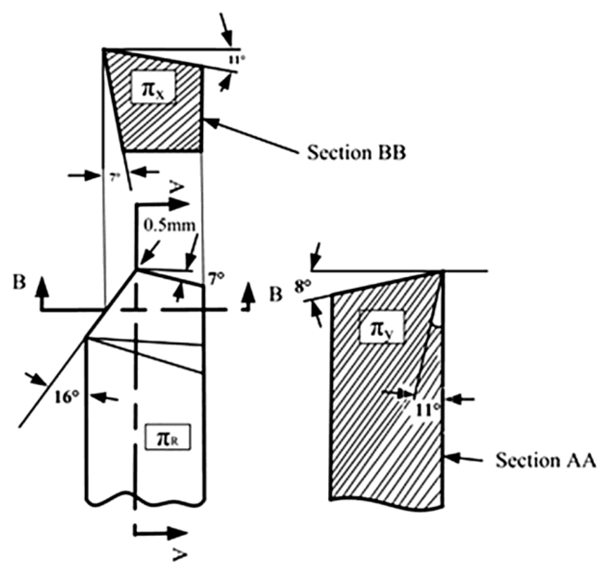


Fig. 2 — ASAS specification of single point cutting tool.

Table 2 — Material composition and hardness of mild steel (A36) work-piece.

| Alloys | C | Mn | Cu | Si | S | P | Fe |
|---|---|---|---|---|---|---|---|
| Composition% | 0.15 | 1.03 | 0.2 | 0.22 | 0.02 | 0.03 | Balance |
| Hardness | 84HRB | | | | | | |

life equation. For ensuring the tool works satisfactorily at a higher cutting velocity, the form stability of the cutting tool could be judged during machining. Cutting velocity always has a definite impact on the form stability of the cutting tool[23]. On the other way the performance of the tool could be assessed, if the cutting force almost remains the same at the same cutting parameters during machining, it indicates the cutting tool retains its shape without changing angles and without any tool failures like tool wear and plastic deformation. In addition to these above factors, lower surface roughness and minimum cutting force are the two significant criteria for product quality, low power consumption, and overall economy of production. In the present investigation, all experiments were conducted using HMT lathe, Model-NH22. For verification of performance of developed centrifugal cast HSSCT within a short duration, intentionally higher cutting velocities were employed for dry turning operation on mild steel workpiece. In the 1st level, the cutting velocity was employed 30 m/min to cut which was the maximum possible working limit for mild steel workpiece and HSSCT under dry condition[24,25]. The other two levels, intentionally higher velocities were employed as 40 m/min in level 2 and 50 m/min in level 3. The purpose was to study the form stability of the tool with increasing cutting velocity resulting increase in temperature. Considering the finish turning, maximum feed and the maximum depth of cut were taken within 0.16 mm/rev and 0.4 mm respectively considering mild steel work piece and HSS cutting tool[25]. The aim of tool development is to resist the higher temperature produces between tool and chip interface during machining and to produce lower surface roughness with low power consumption. The combination of cutting parameters for experimentation was designed using Taguchi orthogonal array (OA). The roughness of the machined workpiece surface was measured using a surface roughness tester (Tayler and Hobson, AMETEK-S100). To measure the cutting force, a tool dynamometer (Kistler, Model-9272) was used.

**2.5 Design and analysis of the experiment**

The cutting parameters are restrained by many factors that are essential to be considered to reach objectives. To get an optimised set of cutting parameters for better output by choosing the classical method of optimisation is very complex. Therefore, a statistical technique was used for determining the optimum cutting parameters which affect the machining process[12-18]. It also helped in modelling and analysing the interaction of factors that decides the output of the machining. Taguchi methodology allows the practitioner to get optimised results with few experimental runs providing a clear understanding of the various nature of the factors. For Taguchi parameter design, the steps follow are selecting OA conducting experiments based on OA, and analyzing the result. The experimental data were examined methodically using the S/N ratio and ANOVA. The S/N ratio analysis provided the optimised combination of process parameters whereas ANOVA analysis examined the contribution of process parameters in percentage on surface roughness and cutting force.

In the Taguchi optimization technique first step is selecting the OA from levels, which consists of the fewest possible combination of parameters required for running the experiment without significantly affecting the outcome. Using OA, the experiment number can be reduced to 50%, which saves the experimental time and cost[26,27]. This technique says if the OA is chosen appropriately, there is no need to run full factorial experiments.

The influence of cutting parameters on the surface roughness and cutting force were analyzed using the S/N ratio, by measuring the deviation of quality characteristics from the desired value. S/N ratio means a signal to noise ratio where the signal corresponds to the required desirable value i.e. mean of the output characteristics and the noise signifies the undesirable value i.e. squared deviation of output characteristics. The goal of the research was to find out the optimum combination of parameters to minimize the surface roughness and to get a lower cutting force. So for these both outputs, the lower is better characteristic was used to optimize the result. According to Yang and Tarang *et al.*[28] the S/N ratio for lower-the-better characteristics can be written as:

$$\frac{S}{N} = -10\log\left[\frac{1}{n}\left(\sum Y^2\right)\right] \quad \ldots (1)$$

where, n presented the total experiment numbers and Y was the observed data.

S/N ratio combined the performance characteristics with the noise factor to calculate the quality of a design and helps to predict the optimum condition for better output. At optimal condition, the S/N ratio can be estimated from Equation 2[28].

$$\eta_e = \eta_m + \sum_{i=1}^{n}(\eta_0 - \eta_m) \quad \ldots (2)$$

$$\eta_e = \eta_m + (A_0 - \eta_m) + (B_0 - \eta_m) + (C_0 - \eta_m) \quad \ldots (3)$$

where, $\eta_e$ is the S/N ratio at optimal condition, n is the number of main design parameters that affect the performance characteristics, $\eta_m$ is the total mean S/N ratio, and $\eta_0$ is the mean S/N ratio at the optimal level. $A_{0,} B_{0,} C_0$ are the average S/N ratio of Vc, f, d respectively when they are in optimum level. A complete experimental procedure for the study centrifugal cast HSSCT is represented in Fig. 3. Minitab-17 software was used for statistical analysis of the Taguchi optimization technique.

ANOVA is done to analyze the significance of each parameter on the performance characteristics. This can be attributed by measuring the total sum of squared deviations ($SS_T$)[19].

$$SS_T = \sum_{i=1}^{m} (\eta_i - \eta_m) \quad \ldots (4)$$

where, m is the number of the experiment, $\eta_i$ is the mean S/N ratio for ith experiment, and $\eta_m$ is the total mean S/N ratio.

## 3 Results and Discussion

This section describes experimental results obtained from experiments based on machining mild steel workpiece in turning operation considering cutting parameters using optimization technique keeping in view to verify the performance of newly developed HSSCT followed by discussion. Further, the experiment conducted using optimized parameters was verified by theoretical prediction. Finally, a comparison of the newly developed HSSCT and the conventional cutting tool was done on the basis of their performance based on the surface roughness of the machined surface of the workpiece and the cutting force required during machining.

### 3.1 Determination of cutting parameters and their effect on surface roughness and cutting force

The cutting parameters levels were decided based on maximum possible working speed of conventional HSSCT on mild steel workpiece and also considering form stability of tool at higher speeds. The three levels selected to get optimum cutting parameters using Taguchi optimization technique are given in Table 3. Cutting velocity, depth of cut and feed rate were taken as three different factors for the optimisation.

$L_9$ OA was used to run the experiment for optimisation of the process parameters. Nine different

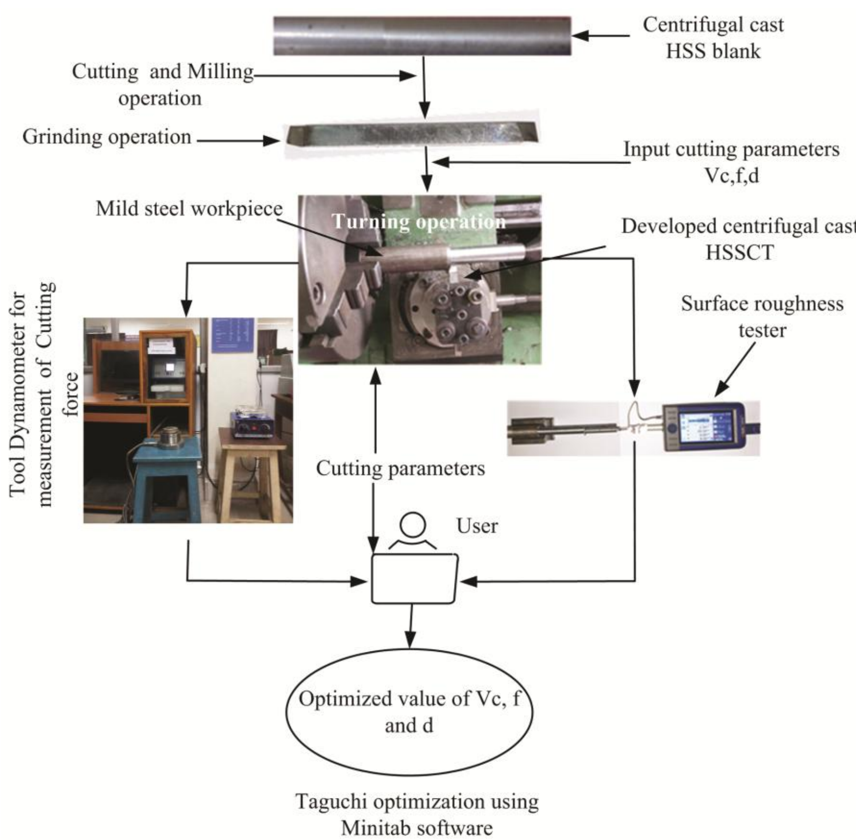


Fig. 3 — Experimental procedure for studying the performance of centrifugal cast HSSCT.

combinations of selected process parameters were designed according to L9 OA as shown in Table 4. Each set of operation was repeated for 3 times to observe surface roughness and cutting force for more accuracy and their averages were considered as the final value. The process parameters were optimised for better output such as surface roughness and required cutting force. To get a better result for surface roughness, five different readings were taken at different places on the machining surface of the workpiece and their averages were noted down. Similarly, cutting forces were measured during the turning operation. Cutting forces generated at each millisecond was noted down. Their averages were considered as the final cutting force. The values obtained from experimental results are shown in Table 5.

The basic concept of the Taguchi optimization technique is to analyze experimental data with the aid of the S/N ratio. A larger S/N ratio value symbolizes the smaller deviation to the output and is considered as the optimum condition. As it is an orthogonal experimental design, the effect of each parameter at different levels could easily be found out. For example, the mean S/N ratio of cutting velocity at levels 1, 2, and 3 can be calculated by finding the mean of S/N ratios of 1-3, 4-6, and 7-9 respectively. The response table for the mean S/N ratio for surface roughness and cutting force is shown in Table 6.

Figures 4 and 5 show the response graph of all the cutting parameters on the basis of smaller is better S/N analysis for lower surface roughness and cutting force respectively. The line between each level represents the effect of the influence of the cutting parameters on the output. The factor levels corresponding to the highest S/N ratio were considered as the optimized value. The ANOVA result for surface roughness and cutting force is shown in Table 7.

### 3.2 Analysis of S/N ratio and ANOVA result for surface roughness

The S/N response table and graph for surface roughness are shown in Table 6 and Fig. 4 respectively. It is known that a greater S/N ratio value indicates less variance of performance characteristic from the targeted value. The optimized result of process variables can be calculated from Fig. 4. The S/N ratio observed for 'Vc' was high at level-2 i-e, 40m/sec. Similarly, f and d had higher S/N values at level-1 (0.04 mm/rev) and level-1 (0.1mm) respectively. Hence, the observed optimal condition for surface roughness was found to be $(Vc)_2$, $f_1$, and $d_1$. ANOVA result for surface roughness is shown in Table 7. According to the result, the feed rate was found to have the maximum effect on surface roughness. Feed rate was found to be (88.40%)

Table 3 — Variables and their levels.

| Factors | Levels | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| Cutting Velocity ($V_c$), m/min | 30 | 40 | 50 |
| Feed rate (f), mm/rev | 0.04 | 0.08 | 0.16 |
| Depth of cut (d), mm | 0.1 | 0.2 | 0.4 |

Table 4 — Experimental design using L9 OA.

| Experiment number | Cutting parameters | | |
|---|---|---|---|
| | Cutting velocity (Vc), m/min | Feed rate (f) rev/min | Depth of cut (d) mm |
| 1 | 30 | 0.04 | 0.1 |
| 2 | 30 | 0.08 | 0.2 |
| 3 | 30 | 0.16 | 0.4 |
| 4 | 40 | 0.04 | 0.2 |
| 5 | 40 | 0.08 | 0.4 |
| 6 | 40 | 0.16 | 0.1 |
| 7 | 50 | 0.04 | 0.4 |
| 8 | 50 | 0.08 | 0.1 |
| 9 | 50 | 0.16 | 0.2 |

Table 5 — Experimental observations and S/N value for surface roughness and cutting force.

| Experiment number | Surface roughness ($R_a$), µm | SNRA For surface roughness | Cutting force (F), N | SNRA for cutting force |
|---|---|---|---|---|
| 1 | 1.77 | -4.95947 | 6.712 | -16.537 |
| 2 | 2.70 | -8.62728 | 15.535 | -23.8262 |
| 3 | 4.05 | -12.1491 | 49.502 | -33.8925 |
| 4 | 1.65 | -4.34968 | 8.130 | -18.2018 |
| 5 | 2.26 | -7.08217 | 30.533 | -29.6954 |
| 6 | 3.45 | -10.7564 | 15.486 | -23.7988 |
| 7 | 2.60 | -8.29947 | 17.307 | -24.7644 |
| 8 | 2.30 | -7.23456 | 8.816 | -18.9054 |
| 9 | 3.78 | -11.5498 | 24.302 | -27.7128 |

Table 6 — Response table of mean S/N ratio for surface roughness and cutting force.

| Cutting parameters | Mean S/N ratio | | | |
|---|---|---|---|---|
| | Level-1 | Level-2 | Level-3 | Max-Min |
| | Surface roughness | | | |
| Cutting velocity(Vc) | -8.579 | -7.396 | -9.028 | 1.632 |
| Feed(f) | -5.870 | -7.648 | -11.485 | 5.616 |
| Depth of cut(d) | -7.650 | -8.176 | -9.177 | 1.527 |
| | Cutting force | | | |
| Cutting velocity(Vc) | -24.75 | -23.90 | -23.79 | 0.96 |
| Feed(f) | -19.83 | -24.14 | -28.47 | 8.63 |
| Depth of cut(d) | -19.75 | -23.25 | -29.45 | 9.70 |

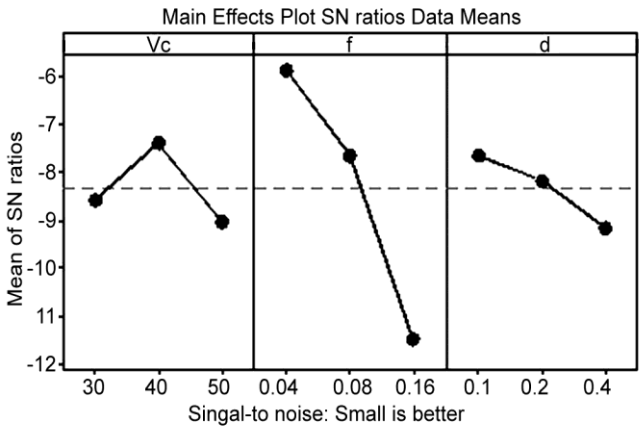


Fig. 4 — The graphic of the mean of S/N ratio versus factor levels (Surface roughness, $R_a$).

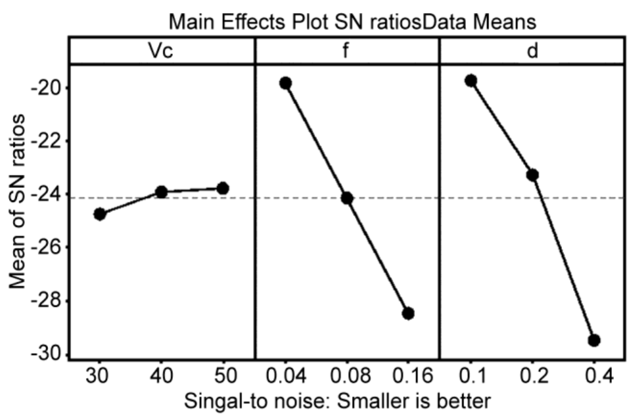


Fig. 5 — The graphic of the mean of S/N ratio versus factor levels (Cutting force, F).

Table 7 — ANOVA table for surface roughness and cutting force.

| Source | DF | Seq SS | Contribution | Adj MS | F-Value |
|---|---|---|---|---|---|
| | | | Surface roughness | | |
| Vc | 2 | 0.52305 | 5.41% | 0.26152 | 9.00 |
| f | 2 | 8.54135 | 88.40% | 4.27067 | 146.90 |
| d | 2 | 0.53986 | 5.59% | 0.26993 | 9.29 |
| Error | 2 | 0.05814 | 0.60% | 0.02907 | |
| Total | 8 | 9.66239 | 100% | | |
| | | | Cutting force | | |
| Vc | 2 | 0.021 | 0.64% | 0.010 | 1.14 |
| f | 2 | 1.482 | 43.03% | 0.740 | 77.24 |
| d | 2 | 1.920 | 55.77% | 0.960 | 100.10 |
| Error | 2 | 0.019 | 0.56% | 0.009 | |
| Total | 8 | 3.443 | 100% | | |

responsible for the surface roughness generation where as cutting velocity and depth of cut contributed (5.41%) and (5.59%) respectively.

Figure 4 shows when the cutting velocity increases, surface roughness starts to decrease upto 40m/min and then increases with further increase in cutting velocity. The lowering of surface roughness value was due to the reduction of built-up-edge (BUE) formation. However, the increase in surface roughness value noticed after 40m/min could be due to the increase in tool nose radius. Also, with the increase in cutting velocity, the heat generated at the shear zone increases making the shearing of the workpiece easier and surface roughness decreases but with further increase in cutting velocity, the tooltip was exposed to excess heat at shear zone started wearing and it leads to increase of surface roughness. With the increase in depth of cut and feed value, it was noticed that surface roughness value started to increase. The main reason for this type of trend is the increase in cutting temperature between tool-workpiece interface due to an increase in friction between tool and workpiece which deteriorated the surface finish and increased the surface roughness. The increase in temperature at the interface reduced the shear strength of the metal and metal became ductile and prone to BUE formation which results in high surface roughness. Therefore, it was recommended to have a lower feed rate with moderate cutting velocity for minimizing surface roughness. The same observation was also observed by Selvaraj, *et al.*[29]. Also, the generally accepted theory states that the surface roughness is directly proportional to the square of feed rate. Therefore, an increase in feed rate resulted in increasing the surface roughness[30]. Usually, mild steel leads to the BUE formation due to its ductile nature which results in raising the surface roughness, burr formation, and lowering the life of the cutting tool. So to avoid all those situations, a lower feed rate and higher cutting velocity should be implemented[31]. When the depth of cut value increased, the contact area of the tool with the workpiece increased resulting in a higher surface roughness value. By applying the optimal condition, minimum surface roughness could be achieved.

**3.3 Analysis of S/N ratio and ANOVA result for cutting force**

Table 6 and Fig. 5 represent the S/N response table and graph respectively for cutting force. A Higher S/N ratio of different process parameters for optimizing cutting force was obtained at Vc (level-3), f (level-1), and d (level-1). ANOVA result for cutting force is shown in Table 7. According to the result, depth of cut had the maximum impact on cutting force with 55.77% followed by feed rate and cutting velocity with 43.03% and 0.64% respectively. From Fig. 5, it can be said that with the increase in 'Vc', the cutting force tends to decrease as the coefficient of at tool-workpiece interface decreases. Also, at a high cutting velocity value, heat generation between the interface increases, reducing the workpiece shear strength and minimizing the cutting force. The above can also be theoretically analysed by the formula

$$F = fd\tau_s F_F \quad \ldots (5)$$

where, $\tau_s$ is the shear stress of the metal, $F_F$ is the form factor and F is the cutting force.

Also, increase in d and f, the tool-workpiece contact increases increasing the cutting force. According to the Taguchi result, the optimal condition for lower cutting force was Vc (50 m/min), f (0.04 mm/rev), and d (0.1mm).

**3.4 Confirmation test**

The optimum cutting parameter obtained from Taguchi analysis were further verified by experimentally and theoretical calculation. The optimum result obtained for minimizing surface roughness was $V_{c2}$, $f_1$, $d_1$. Similarly, the optimal result for minimizing cutting force was predicted as $Vc_3$, $f_1$, $d_1$. Based on these parameters, experiments were conducted. The measured value of surface roughness and cutting force are shown in Table 8. The experimental result obtained from experiments using optimum cutting parameters for surface roughness was 1.6µm. Similarly, using optimum cutting parameters for force was 5.82N. The predicted S/N ratio at optimal conditions can be calculated using Equation 3. From the calculated S/N ratio, the cutting force and surface roughness value were easily calculated using Eq. 1. Table 8 shows the comparison between the predicted and experiment value of surface roughness and cutting force at optimized cutting conditions. It can be seen that the surface roughness value and cutting force value obtained from the experiment were very close to the calculated value and in confidence interval level (CI). The CI value in dB at 95% confidence level for both cases was found out using Eqs 6 and 7[32,33].

$$CI = \sqrt{F_\alpha(1, v_e)V_e\left(\frac{1}{\eta_{eff}} + \frac{1}{r}\right)} \quad \ldots (6)$$

$$\eta_{eff} = \frac{N}{1+v_T} \quad \ldots (7)$$

where, N stands for total experimental numbers, $v_e$ corresponds to the error DOF and $v_T$ is the DOF of variables. $r$ is the number of confirmation experiments conducted and $V_e$ is the error variance. The surface roughness (1.6µm) and cutting force (5.82N) value observed were in the calculated confidence interval level. The interval for surface roughness and cutting force was calculated as 1.49-1.78 µm and 5.41N-5.97N respectively. In both cases, the experimental data fell within the CI region.

Table 8 — Experimental and predicted data for optimized cutting condition.

| | Optimal cutting parameters | |
|---|---|---|
| | Predicted result | Experimental result |
| Surface roughness | | |
| Parameter level | $V_{c2}f_1d_1$ | $V_{c2}f_1d_1$ |
| Surface roughness (µm) | 1.63 | 1.6 |
| S/N ratio (dB) | -4.256 | -4.093 |
| Cutting force | | |
| Parameter level | $V_{c3}f_1d_1$ | $V_{c3}f_1d_1$ |
| Cutting force (N) | 5.68 | 5.82 |
| S/N ratio (dB) | -15.09 | -15.343 |

**3.5 Comparison between centrifugal cast HSSCT and conventional HSSCT**

***3.5.1 Cutting force and surface roughness***

Experiments were carried out for turning mild steel work-pieces using centrifugal cast HSSCT and conventional HSSCT having the same tool geometry. The composition and hardness of the conventional HSS tool are given in Table 9. The cutting parameters were selected from OA. Figure 6 (a and b) shows the comparison between conventional HSS and centrifugal cast HSS tools on the basis of surface roughness and cutting force respectively. Experimental results showed that the surface roughness and cutting force value of centrifugal cast HSSCT was found very closer to the conventional HSS tool.

Generally, surface roughness obtained during turning operation comes under 0.6 to 6 µm. Surface roughness measured in these experiments for finish turning operation came within 1.6 to 3.2 µm. The little variation in surface roughness encountered could be variation in tool geometry during turning operation. Surface roughness was affected by many factors during machining such as machining conditions, machining parameters, cutting tool, and work-piece

Table 9 — Composition and hardness of conventional HSS tool (HSS M2).

| Elements | C | Si | Mn | P | S | Cr | Mo | V | W | Fe |
|---|---|---|---|---|---|---|---|---|---|---|
| Composition % | 0.78-0.88 | 0.2-0.4 | 0.2-0.4 | 0.35 | 0.35 | 3.75-4.5 | 4.5-5.5 | 1.6-2.2 | 5.5-6.75 | rest |
| Hardness | 61HRC | | | | | | | | | |

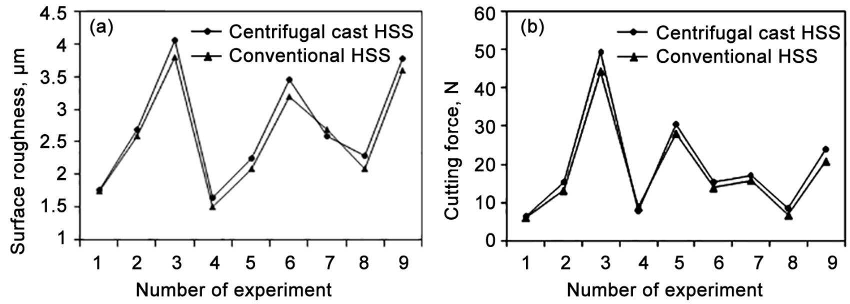


Fig. 6 — Comparison between centrifugal cast HSSCT and conventional HSSCT on the basis of (a) surface roughness, and (b) cutting force.

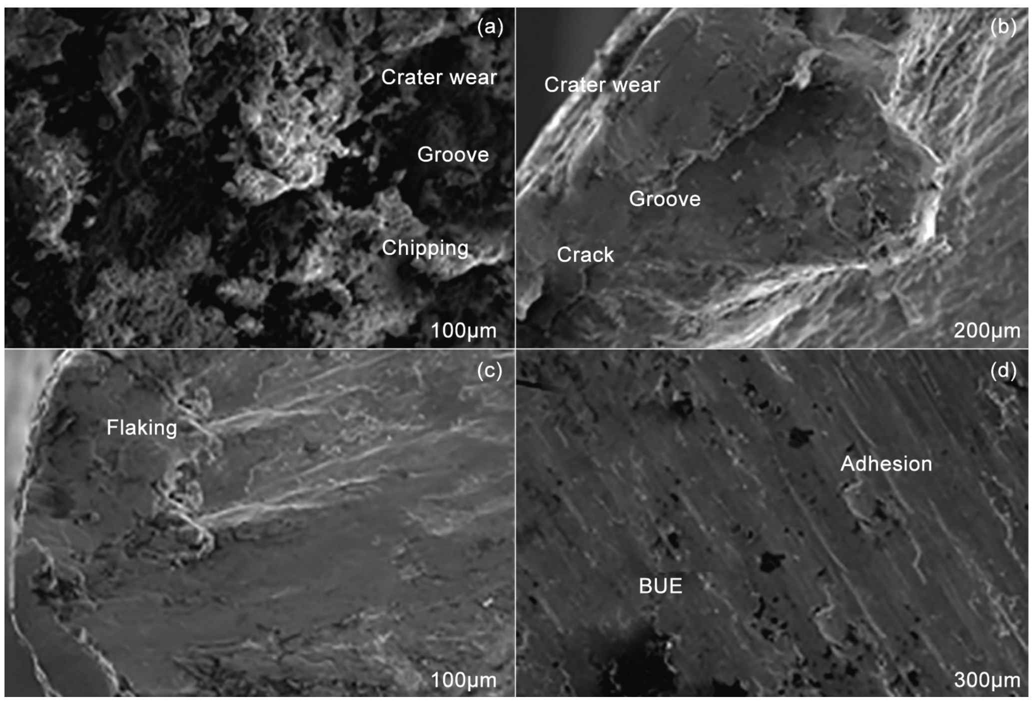


Fig. 7 — SEM image at the optimal cutting condition for minimizing cutting force (a) centrifugally cast HSSCT, (b) conventional HSSCT, and SEM image at the optimal cutting condition for minimizing surface roughness condition, (c) centrifugally cast HSSCT, and (d) conventional HSSCT.

material[34]. At a constant feed, surface roughness is inversely proportional to nose radius. According to Neseli *et al.*[35] tool nose radius is the dominant factor on the roughness of the surface. An increase in nose radius during machining decreases surface roughness. However, there is a certain limit to nose radius, further, an increase in nose radius leads to an increase in cutting forces and tool wear, which increases the surface roughness.

#### *3.5.2 Tool wear analysis at optimum conditions*

Tool wear analysis of centrifugal cast HSSCT and conventional HSSCT single point cutting tool was carried out at optimal cutting parameters for minimum surface roughness and cutting force condition obtained using centrifugal cast HSSCT to compare the difference in wear condition at the same value of process parameters. A cutting time of 70 min was set for both the tools maintaining the cutting parameters identical for both the tools. Their worn surfaces were observed using the Scanning electron microscope. At the optimal condition of minimizing cutting force, i-e, ($Vc_3$,$f_1$,$d_1$), tool wear observed were more comparable to the optimized condition for minimizing surface roughness ($Vc_2$,$f_1$,$d_1$) for both conventional and centrifugal cast tools. The result obtained was due to the higher cutting velocity level (50 m/min) at optimal cutting force conditions. According to Taylor's tool life equation, higher cutting velocity results in increase in tool wear rate. The rise in cutting velocity increased the temperature at the tool-workpiece interface resulting in thermal softening and notching of the tool. Crater wear observed for both the tools is presented in Fig. 7. Flank wear and crater wear values

Table 10 — Crater wear and flank wear value at optimum cutting conditions for centrifugal cast HSSCT and conventional HSSCT.

| Wear | Centrifugal cast HSSCT | | Conventional HSSCT | |
|---|---|---|---|---|
| | $V_{c3}f_1d_1$ | $V_{c2}f_1d_1$ | $V_{c3}f_1d_1$ | $V_{c2}f_1d_1$ |
| Crater wear (KB), mm | 1.7 | 0.8 | 0.98 | 0.5 |
| Flank wear (VB), mm | 0.21 | 0.1 | 0.18 | 0.09 |

at each cutting condition for every tool is presented in Table 10.

From the Table 10, it can be noticed that centrifugally cast HSSCT has a slight increase in wear rate at each cutting condition than that of the conventional HSSCT. However, the flank wear rate of centrifugal cast HSSCT is comparable to that of the conventional tool. SEM images reveal grooving and adhesive wear took place in both cutting conditions for conventional tools. Similarly, chipping, flaking, and grooving were the main criterion of tool wear observed for centrifugal cast HSSCT. Continuous chips produced for centrifugal cast HSSCT and comparatively lower tool hardness might be the reason for the above.

## 4 Conclusions

The cutting ability of centrifugally cast single point cutting tool using scrapped tools and the same of conventional HSS single point cutting tool brought from the market, with identical tool geometry, are compared. Also, the wear characteristics of both the tools are analysed at length. The following conclusions are arrived at:

(i) Centrifugal casting methods offer viable techniques for the development of single point cutting tools from scrapped tools.

(ii) The 'feed rate' significantly affects the surface roughness of the work-piece followed by 'depth of cut' and 'cutting velocity' taken in that order.

(iii) The 'depth of cut' significantly affects the cutting force requirements followed by feed rate and cutting velocity taken in that order.

(iv) The performance of the developed tool is comparable with that of the conventional HSS cutting tool.

(v) Tool wear of both the tools with identical tool geometry is comparable under the experimental conditions.

From the above observation, it is noticed that despite having a comparatively lower hardness value compared to the conventional HSS tool, the newly developed tool is able to meet the required output for the machining operations. The variation in the roughness of the machined surface and cutting force generated is not significant compared to the conventional tool. Also, an important step such as the forging process can be avoided as the centrifugal casting process is advantageous for generating dense and fine grain structure with directionality in a cast product.

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