Investigation on dry machining of stainless steel 316 using textured tungsten carbide tools

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Abstract
In this research, austenitic stainless steel SS316 material has been machined using textured carbide cutting tools under dry conditions. Micro-textures were made on tool rake face using wire spark erosion machining technology. Effects of three important machining process parameters i.e. cutting speed, depth of cut and feed rate on machinability (MRR, average roughness, and tool wear) of SS316 have been investigated. Taguchi L27 orthogonal array based twenty seven experiments have been carried out by varying machining parameters at three levels. Feed rate has been identified as the most important parameter. Machining parameters have been optimized by grey entropy method to enhance the machinability. Optimal combination of machining parameters i.e. 170 m min\(^{-1}\) cutting speed, 0.5 mm/rev feed rate and 1.5 mm depth of cut produced the best machinability with 3.436 \(\mu\)m average roughness, 105187 mm\(^3\) min\(^{-1}\). MRR, and tool wear 234.63 \(\mu\)m. Lastly, a tool wear and chip morphology study have been done where textured tools have been found outperformed (Non-textured) tools.

1. Introduction
There are different grades of stainless steel used to fulfil specific application requirements. Austenitic chromium-nickel stainless steel SS316 is a prime candidate material for heat exchangers, furnace parts, jet-engine parts, and chemical processing and pharmaceutical equipment etc [1, 2]. Excellent toughness, superior strength, and high corrosion resistance etc are the special characteristics of SS 316. It undergoes extensive machining operations while producing the aforementioned parts and equipment. But its machining by conventional processes is challenging and results in poor machinability in terms of frequent tool wear, deteriorated work surface quality, high consumption of lubricants, escalated machining cost, and high environmental footprints [3, 4]. To address these challenges, many efforts as regards to research and development and innovations have been made such as using green lubricants and sustainable lubrication techniques (i.e. minimum quantity lubrication, dry cutting, cryogenic machining), machining with the assistance of vibration and heat source, using treated and coated tools, intelligent modelling and optimization of parameters etc [5, 6]. It is noticed from the literature that textured tools have potential to reduce tool wear and prolong tool life [7, 8]. Textures on rack and flank face help to reduce the cutting forces and friction, and thereby reduce the heat generation, which further improves tool’s performance. Texturing on cutting tools also affects the chip adhesion and improves the effectiveness of lubrication and tool-chip contact length. There are few available articles provide superficial understanding of machining of steels with textured tools [8–10]. It was reported that textures created by laser machining on rake face of carbide tool outperformed plain carbide tool for machining of AISI 316 stainless steel [9]. Similar results were found during the machining of AISI 52100 by textured Al\(_2\)O\(_3\)/TiCN ceramic cutting tool on rake face and plain ceramic cutting tool, where textures were developed by wire-EDM process [3]. Moreover, other machining processes were also used for creating the texture on tool such as electro chemical machining and abrasive jet machining etc [10]. There are some investigations on utilizing optimum techniques as well for machinability enhancement of various engineering materials. In a study, the optimum values of process parameters namely cutting speed, feed rate and depth of cut.
were obtained using grey relational with Taguchi method for the machining of Inconel 825 [7]. This set of techniques was also used for machining of AISI 1040 steel with carbide coated tool under dry conditions [8, 9]. Grey relational with response surface technique was implemented to get the best combinations depth of cut, spindle speed, width of cut and feed rate for the better material removal rate with surface roughness during the milling process. In addition, the highest value of grey relation grade was considered to identify the best combination process parameters [10]. ANOVA based grey relational technique was used for optimum setting of machining parameters for 15–5 PH stainless steel [11].

There is a scarcity of work on textured tool based machining and machinability investigation of stainless steel material. Therefore, to fill the research gap, an attempt is made in the present work to machine SS316 using textured cutting tools under dry environment and to investigate and optimize its machinability. Authors have selected a tungsten carbide cutting tool with an objective to facilitate the small scale machinists and manufacturers who probably can afford this tool based on its cost economy. Textures have been made on the rack face of Tungsten carbide cutting tool inserts to machine SS316. Various settings of machining parameters have been obtained by Taguchi L27 design of experiment technique. The effects of machining parameters on material removal rate and average surface roughness under the influence of dry conditions have been investigated. Further, parameters have been optimized by grey relational technique to get the best machinability. The subsequent section of this paper discusses the machining process and results of investigation.

2. Experimental details

Austenitic stainless steel SS316 has been machined on conventional Lathe (Model No. COLCHESTER Mascot 1600) under dry condition using textured tungsten carbide cutting tool (TNMG-160408–45) insets having geometry 6°–6°–6°–6°–15°–75°–0.8 mm. Figure 1 depicts the experimental setup and sequence of steps followed in the present work. The overall work plan consists of machining of SS316 at various combinations of process parameters during experimentation stage, followed by measurement of machinability indicators i.e. MRR and $R_a$, analysis of the effects of machining process parameters on MRR and $R_a$, optimization of process parameters to obtain the best values of MRR and $R_a$, and lastly characterization of chip morphology and tool wear mechanisms for a comparison between textured and plain tools. Important process parameters i.e. cutting speed, feed rate, and depth of cut have been varied at three levels (table 1). A total of twenty seven experiments have been designed and conducted based on Taguchi robust design of experiment technique with $L_{27}$ orthogonal array. The levels of machining parameters have been determined based on some preliminary experiments, machine constraints and literature review. Each experiment was conducted for a time period of seven minutes. Texturing on rack face of the cutting tools is done by wire spark erosion machining (wire-EDM/WEDM) process. Average surface roughness $R_a$ and material removal rate (MRR) have been considered as machinability indicators or responses. $R_a$ is measured using handheld surface profiler TMteck makesTMR200. While, MRR has been evaluated using the following equation-
Moreover, a scanned electron microscopic study has also been done to analyse the tool wear mechanisms and chip morphology.

3. Results and discussion

Table 2 presents all twenty-seven combinations of machining parameters and corresponding values of machinability indicators i.e. Ra and MRR. Further, the effects of machining parameters on Ra and MRR are discussed here as under.

3.1. Analysis of surface roughness

The influence of selected process parameters on average roughness is analysed and discussed in this section. Figures 2(a)–(c) presents the variation of average roughness with machining parameters. It is observed that at maximum cutting speed of magnitude 170 m min\(^{-1}\) with 0.15 mm/rev feed rate and 1 mm depth of cut, minimum roughness value 0.541 \(\mu m\) is obtained. Whereas, at the same cutting speed with increasing rate of feed and depth of cut 0.2 mm/rev and 1.5 mm respectively, the roughness value increased to 4.476 \(\mu m\). From the graph it is clear to confirm the surface roughness is completely dependent on the tool feed rate. At 70 m/min cutting speed value, the average roughness varies from 0.638 \(\mu m\) for 0.15 mm/rev and 4.08 \(\mu m\) for 0.5 mm/rev. In case of machining at other cutting speed too, the roughness was found to have increasing trend.

Material removal rate = Cutting speed \times Feed rate \times Depth of cut

\[ (1) \]

Table 1. Details of process parameters and material composition.

| Input parameters         | Level 1 | Level 2 | Level 3 |
|--------------------------|---------|---------|---------|
| Cutting speed (m/min)    | 70      | 120     | 170     |
| Feed rate (mm/rev)       | 0.15    | 0.2     | 0.5     |
| Depth of cut (mm)        | 0.5     | 1       | 1.5     |
| Composition of SS316 (Weight) | Cr-16%–18%, Ni-10%–14%, Mo- 2%–3%, K-0.045%, S-0.030%, C-0.08%, N-0.10%, Mg- 2%, Si- 0.75%, Fe- balance |

Table 2. Experimental combinations and responses.

| Run no. | Cutting speed (m/min) | Feed (mm/rev) | Depth of cut (mm) | Average roughness \(R_a(\mu m)\) | Material removal rate (mm\(^3\)/min) |
|---------|-----------------------|---------------|-------------------|-------------------------------|-----------------------------------|
| 1       | 120                   | 0.2           | 1                 | 0.745                         | 24 000                            |
| 2       | 70                    | 0.2           | 1                 | 1.096                         | 14 000                            |
| 3       | 120                   | 0.15          | 0.5               | 0.963                         | 9000                              |
| 4       | 120                   | 0.15          | 1                 | 0.852                         | 18 000                            |
| 5       | 170                   | 0.15          | 1.5               | 0.821                         | 38 250                            |
| 6       | 70                    | 0.15          | 1                 | 0.683                         | 10 500                            |
| 7       | 120                   | 0.15          | 1.5               | 0.776                         | 27 000                            |
| 8       | 120                   | 0.2           | 1.5               | 0.783                         | 36 000                            |
| 9       | 170                   | 0.15          | 0.5               | 0.750                         | 12 750                            |
| 10      | 70                    | 0.15          | 1.5               | 0.731                         | 15 750                            |
| 11      | 170                   | 0.5           | 1                 | 3.152                         | 85 000                            |
| 12      | 120                   | 0.5           | 0.5               | 4.190                         | 30 000                            |
| 13      | 120                   | 0.5           | 1.5               | 4.227                         | 90 000                            |
| 14      | 170                   | 0.2           | 1                 | 1.917                         | 34 000                            |
| 15      | 70                    | 0.5           | 1                 | 4.089                         | 35 000                            |
| 16      | 120                   | 0.2           | 0.5               | 4.107                         | 12 000                            |
| 17      | 70                    | 0.5           | 1.5               | 3.398                         | 52 500                            |
| 18      | 70                    | 0.2           | 0.5               | 1.744                         | 7000                              |
| 19      | 120                   | 0.5           | 1                 | 3.116                         | 60 000                            |
| 20      | 70                    | 0.15          | 0.5               | 1.279                         | 5250                              |
| 21      | 70                    | 0.2           | 1.5               | 1.265                         | 21 000                            |
| 22      | 170                   | 0.2           | 1.5               | 4.476                         | 51 000                            |
| 23      | 170                   | 0.5           | 1.5               | 3.436                         | 105 187                           |
| 24      | 170                   | 0.15          | 1                 | 0.541                         | 25 500                            |
| 25      | 170                   | 0.5           | 0.5               | 3.619                         | 42 500                            |
| 26      | 170                   | 0.2           | 0.5               | 0.811                         | 17 000                            |
| 27      | 70                    | 0.5           | 0.5               | 4.016                         | 17 500                            |
with increase in feed rate. Advancement of the cutting tool with reference to the cutting path is feed rate and it also depends on the cutting speed. At minimum feed rate, the advancement of cutting tool will be slow and tends to remove bulk proportionally. At higher feed rate, the tool travels fast and produced roughness surface with improper removal of bulk. The stainless steel material will plastically deform and tends to adhere over rake face of the hard cutting tool. Over a time of period, the build-up edge on the cutting tool will support to change the geometrical cutting phenomena in terms of shear, temperature and friction at higher end. Therefore the rapid growth in build-up edge (maximum wear) will cause rougher surface.

3.2. Analysis of MRR

The variation of MRR with machining parameters is shown in figures 3(a)–(c). It is observed that at lower cutting speed (i.e. 70 m/min), the maximum amount of material removed from the workpiece is 51 843 mm³ min⁻¹ at a process condition of 0.5 mm/rev feed rate and 1.5 mm depth of cut. For the same cutting speed, the minimum

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Figure 2. Effects of process parameters on average surface roughness.
material removal ($4790 \text{ mm}^3 \text{ min}^{-1}$) took place at 0.15 mm/rev feed rate and 0.5 mm depth of cut. Therefore, it can be said that the amount of material removal is significantly dependent on feed rate followed by depth of cut. The variations in material removal for 0.15 mm/rev and 0.2 mm/rev are almost similar. When calculating the material removal rate, the maximum amount of bulk metal removed is 105 187 mm$^3$ min$^{-1}$ at same cutting speed of 170 m min$^{-1}$. It is noticed that MRR is increasing with the increment of feed rate, because at higher feed rate tool is moving fast towards the workpiece and remove more amount of material from the surface of workpiece [14]. Similarly, with increase in depth of cut, the amount of bulk material removal will be maximum and hence the MRR will be higher.

The aforementioned discussion on variation of machining parameters on Ra and MRR indicates towards a trade-off and prompts to go for optimization of machining parameters to attain the best values of machinability indicators at a single set of process parameters.

Figure 3. Effects of process parameters on material removal rate.
**3.3. Optimization**

To obtain the best set of machining parameters, a multi-response optimization is done using grey-relational technique, which is an important statistical optimization technique having a previous track record for successful optimization of manufacturing processes [15]. In the current work, entropy based grey relational technique (GAT) has been used to find the optimal solution.

It is an analytical optimizations technique which provides appropriate tools for examine a rank of order of multiple objects with resemblance from an objective [15]. It requires less information to predict the behaviour of discrete data problem and an uncertain system. If number of experiments range is more, the factors are effaceable; hence data pre-processing which is a significant step to manage the factors of GTA is required to be done [16]. Lower the better for roughness and higher the better for MRR were used for data pre-processing in the present study. In addition entropy measurement techniques used as an objective weighting technique. Discrete type of entropy is used in grey entropy measurement for properly conduct weighting analysis [17].

The objective functions are framed with surface roughness and material removal rate having equal weightage – influencing both surface roughness and material removal rate. The values of Ra and MRR at -1, 0.5 mm/rev and 1.5 mm depth of cut. It is the optimum condition to cut austenitic stainless steel SS316 using tungsten carbide textured cutting tool.

To study the influence of process parameters on GRG, counter plots are made and as shown in figures 4(a)–(c). It is to note that the maximum value of GRG exhibits the best combination of process parameters [10]. It can be observed from figure 4(a) that the best solution can be achieved with the feed rate in the range of 0.3 to 0.45 mm/rev at any cutting speed. Furthermore, as shown in figure 4(b), there is not much influence of depth of cut on GRG and its values from 0.75 to 1 mm influence GRG at some extent. In essence, feed rate is the predominant factor influencing both surface roughness and material removal rate. The values of Ra and MRR at optimal machining conditions are 3.436 μm and 105 187 mm2 min−1 respectively. Further, an extra experiment has been conducted where SS316 is machined under dry conditions and at the aforementioned optimum

### Table 3. Calculation of optimization techniques.

| Run | Material removal rate | Surface roughness | GRG |
|-----|------------------------|-------------------|-----|
|     | Nor. | Dev. | GRC | x/d | f(x/d) | Nor. | AR | AR | x/d | f(x/d) |
| 1   | 0.153 | 0.847 | 0.371 | 0.033 | 0.112 | 0.948 | 0.052 | 0.906 | 0.052 | 0.176 | 0.639 |
| 2   | 0.072 | 0.928 | 0.350 | 0.031 | 0.105 | 0.859 | 0.141 | 0.780 | 0.045 | 0.152 | 0.565 |
| 3   | 0.031 | 0.969 | 0.340 | 0.030 | 0.103 | 0.893 | 0.107 | 0.823 | 0.047 | 0.160 | 0.582 |
| 4   | 1.014 | 0.896 | 0.358 | 0.032 | 0.108 | 0.921 | 0.079 | 0.864 | 0.049 | 0.168 | 0.611 |
| 5   | 0.270 | 0.750 | 0.406 | 0.036 | 0.122 | 0.929 | 0.071 | 0.875 | 0.050 | 0.170 | 0.641 |
| 6   | 0.043 | 0.957 | 0.343 | 0.030 | 0.103 | 0.964 | 0.036 | 0.933 | 0.033 | 0.181 | 0.638 |
| 7   | 0.178 | 0.822 | 0.378 | 0.033 | 0.114 | 0.940 | 0.060 | 0.893 | 0.031 | 0.174 | 0.636 |
| 8   | 0.252 | 0.748 | 0.400 | 0.035 | 0.121 | 0.938 | 0.062 | 0.890 | 0.031 | 0.173 | 0.645 |
| 9   | 0.061 | 0.939 | 0.348 | 0.031 | 0.105 | 0.947 | 0.053 | 0.904 | 0.032 | 0.176 | 0.626 |
| 10  | 0.086 | 0.914 | 0.354 | 0.031 | 0.107 | 0.952 | 0.048 | 0.912 | 0.052 | 0.177 | 0.653 |
| 11  | 0.652 | 0.348 | 0.590 | 0.052 | 0.178 | 0.336 | 0.664 | 0.430 | 0.025 | 0.084 | 0.510 |
| 12  | 0.202 | 0.798 | 0.385 | 0.034 | 0.116 | 0.073 | 0.927 | 0.350 | 0.020 | 0.068 | 0.368 |
| 13  | 0.693 | 0.307 | 0.620 | 0.055 | 0.187 | 0.063 | 0.937 | 0.348 | 0.020 | 0.068 | 0.484 |
| 14  | 0.235 | 0.765 | 0.395 | 0.035 | 0.119 | 0.650 | 0.350 | 0.588 | 0.034 | 0.114 | 0.492 |
| 15  | 0.243 | 0.757 | 0.398 | 0.035 | 0.120 | 0.098 | 0.902 | 0.357 | 0.020 | 0.069 | 0.377 |
| 16  | 0.035 | 0.945 | 0.346 | 0.031 | 0.104 | 0.994 | 0.906 | 0.356 | 0.020 | 0.069 | 0.351 |
| 17  | 0.387 | 0.613 | 0.449 | 0.040 | 0.135 | 0.274 | 0.726 | 0.408 | 0.023 | 0.079 | 0.428 |
| 18  | 0.014 | 0.986 | 0.337 | 0.030 | 0.101 | 0.694 | 0.306 | 0.621 | 0.035 | 0.121 | 0.479 |
| 19  | 0.448 | 0.552 | 0.475 | 0.042 | 0.143 | 0.346 | 0.654 | 0.433 | 0.025 | 0.084 | 0.454 |
| 20  | 0.000 | 1.000 | 0.333 | 0.030 | 0.100 | 0.812 | 0.188 | 0.727 | 0.042 | 0.141 | 0.530 |
| 21  | 0.129 | 0.871 | 0.365 | 0.032 | 0.110 | 0.816 | 0.184 | 0.731 | 0.042 | 0.142 | 0.548 |
| 22  | 0.374 | 0.626 | 0.444 | 0.039 | 0.134 | 0.000 | 1.000 | 0.333 | 0.019 | 0.065 | 0.389 |
| 23  | 1.000 | 1.000 | 1.000 | 0.089 | 0.301 | 0.264 | 0.736 | 0.405 | 0.023 | 0.079 | 0.702 |
| 24  | 0.166 | 0.834 | 0.375 | 0.033 | 0.113 | 1.000 | 0.000 | 1.000 | 0.057 | 0.194 | 0.687 |
| 25  | 0.305 | 0.695 | 0.418 | 0.037 | 0.126 | 0.218 | 0.782 | 0.390 | 0.022 | 0.076 | 0.404 |
| 26  | 0.096 | 0.904 | 0.356 | 0.032 | 0.107 | 0.931 | 0.069 | 0.879 | 0.050 | 0.171 | 0.618 |
| 27  | 0.100 | 0.900 | 0.357 | 0.032 | 0.108 | 0.117 | 0.883 | 0.362 | 0.021 | 0.070 | 0.359 |

Where, Nor. = Normalization of data with respect to higher the better for MRR and lower the better for surface roughness. Dev. = Deviation sequence and GRC is the Grey relation coefficient.
parameters using a non-textured or plain cutting tool and the values of responses found are $R_a = 4.526 \, \mu m$ and $MRR = 105 \, 187 \, mm^3 \, min^{-1}$. Since, it is known that the values of MRR as obtained using equation (1), which is same in case of both, textured and plain tools. Therefore, to assess cutting tool (textured and non-textured) performances, machining parameter combinations for maximum and minimum roughness at run numbers 22 and 24 respectively have been considered to make further comparison.

3.4. Tool wear study
To confirm the results of optimization and to make a comparative evaluation between textured and plain tools, investigations on tool wear morphology along with chip morphology have also been done. Figure 5 shows the
flank wear of the cutting tools observed on machining stainless steel with reference to (i) minimum average roughness, (ii) optimum result and (iii) maximum roughness. From the experimental results, it is clear that at a minimum feed rate, 0.541 μm in surface roughness and 25 500 mm³ min⁻¹ MRR as the lowest results can be achieved with a minimum tool wear 180.96 μm. Similarly for a maximum surface roughness of 4.476 μm and MRR 51 000 mm³ min⁻¹ was achieved with maximum tool wear of 269.17 μm. However, the optimal result.
obtained from the hybrid method shows an average wear of 234.63 μm with an ideal result on machinability (table 4). The wear mechanism at optimal machining condition is due to friction and chipping of hard metal. While machining at 0.2 mm/rev and 1.5 mm depth of cut the cutting energy induced the metal to fuse and adhere over rake face as a weldment. Thickness of this adhesive wear is around 210 μm beyond the fraction of flank face. Experiments with minimum depth of cut and feed rate (1 mm and 0.15 mm/rev) have produced minimum tool wear of 180 μm with a same cutting speed of 170 m min⁻¹. These results are similar to the machinability investigation of SS304 reported in [12]. In this condition, the amount of force induced to cut the bulk material has been reduced and minimum Rₚ/MRR was achieved. To study the process response in detail, the flank wear, material removal and chips produced at proposed condition are correlated. For the average and minimum tool wear, the chip removed from the bulk is continuous and MRR are significantly varying. At high machining rate, the weldment produced over the crater has induced the metal removal rate to hike and the stress induced on cutting has yielded the metal chip to produce in the form of serration (discontinuous) chips. Therefore, it has been confirmed that, at an optimal cutting condition can produce best result even the speed does not varied.

In depth investigation reveals that, the plain cutting tool has been forced to severe tool wear with ridges and grooves, as shown in figures 5(d)–(f). While, comparing the same with textured cutting tool, severity in wear found less with built up edge over the cutting nose as shown in figures 5(a)–(c). In plain cutting tool, the material deformation and shearing bulk removed yields to produce continuous chip with sharp edges (figures 6(a)–(b)). The mechanical action between the sharp continuous chip and tool interface cause ridged and grooves over the cutting edge. However, in textured cutting tool, the wear mechanism is in adhesion (in the form of built—up edge) due to plastic deformation of material welded over the step pattern. The built up edge induce the bulk deformed from ductile—to—brittle transformation and led to produce serrated metal chips (figures 6(c)–(d)). Therefore, the textured tool has better life compared to plain tool with good surface roughness. This can also be controlled with suitable process parameters and machining conditions.

### 4. Conclusions

Investigation on machinability of SS316 under dry machining using textured carbide tools is reported in this paper. The following conclusions can be drawn from this research work:

- The average roughness measured is highly influenced by the feed rate and the best value of average roughness 0.541 μm was achieved while machining stainless steel 316 at high speed (170 m min⁻¹) cutting with an average feed rate of 0.15 mm/rev.
- The maximum material removal obtained is 105 187 mm³ min⁻¹ at 170 m min⁻¹, 0.5 mm/rev and 1.5 mm depth of cut. While comparing average roughness and MRR the individuality of feed rate and depth of cut has highly contributed.
- The set of optimum process parameters for multi objective function of ideal response for Rₚ and MRR is 170 m min⁻¹ cutting speed, 0.5 mm/rev feed rate and 1.5 mm depth of cut. In addition, the tool flank wear of 230 μm has been obtained.
- Therefore, it has been suggested that machining of hard material at higher speed with an average feed rate and depth of cut can produced ideal machining condition as a solution to secure the best machinability.
- While comparing the performances of textured and plain cutting tools, abrasive wear mechanism was noticed in plain cutting tool and adhesive wear on textured nose. Due to adhesion built—up edge was found at tool tip to produce discontinuous chip on machining process.

| Machining conditions | Cutting speed (m/min) | Feed (mm/rev) | Depth of cut (mm) | Average roughness (μm) | Tool wear (μm) |
|----------------------|-----------------------|--------------|-----------------|----------------------|----------------|
|                      |                       |              |                 | Textured tool  | Plain tool   | Textured tool | Plain tool   |
| For minimum          | 170                   | 0.15a        | 1               | 0.541             | 1.98          | 180.96       | 240.32       |
| roughness            |                       |              |                 |                      |               |              |              |
| For optimum          | 170                   | 0.5b         | 1.5             | 3.436             | 4.526         | 234.63       | 298.61       |
| roughness            |                       |              |                 |                      |               |              |              |
| For maximum          | 170                   | 0.2c         | 1.5             | 4.476             | 5.612         | 269.17       | 350.45       |
| roughness            |                       |              |                 |                      |               |              |              |
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