Effect of Machining Parameters on Tool Life and Surface Roughness of AISI 1040 Dual Phase Steel

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The purpose of this research is to investigate the effect of heat treatment parameters on the tool life and surface roughness of dual phase steel. Optimization of machining parameters (cutting speed, feed and depth of cut) is carried out for the machinability tests on medium carbon low alloy steel. Taguchi’s method of design is used to carry out machinability tests. Analysis of variance (ANOVA) is carried out to determine the relative contribution of machining parameters on tool life and surface roughness. Microstructure analysis is carried out to ascertain the machining behavior of the steel. Results have shown that, depth of cut and cutting speed are the most significant factors contributing on the variation of the tool life and surface roughness. Optimized machining parameters are calculated in order to obtain higher tool life and lower surface roughness value.

Keywords: Ferrite, bainite, martensite, dual phase, AISI1040.

1. Introduction

Machinability of material plays an important role in the industry to improve their manufacturing capacity and to reduce the cost of the component. Dual phase microstructure in a medium carbon and/or alloyed steel provides not only a high strength, but also a good formability and yielding without serrations. In this type of microstructure, soft ferrite and hard martensite phases are present which induces the ductility and the strength for the steel. The medium carbon low steel property can be easily altered by giving suitable heat treatment process. Heat treatment process involves the heating, soaking, holding and cooling in different temperature and coolants. The improvement in the mechanical properties via forming a dual phase microstructure in the steel supplies the benefit of reducing the weight of systems. The studies on dual phase steels (DPS) have been focused generally on the microstructural and mechanical characterizations after intercritical heat treatment applications. On the other hand, the machinability of these materials is also very important property which should be focused on.

Especially low carbon and medium carbon steel may be produced with dual phase structure. During heat treatment, it is possible to alter the mechanical properties of the material by obtaining the suitable microstructure as per the requirements. Iron has a higher solubility for carbon in the austenite phase. Formation of dual phase in medium carbon steel depends on the intercritical temperature range. Dual phases may be ferrite with martensite (F-M) or ferrite with a bainite (F-B). Generally, in a dual phase condition, hardness property will increase due to the increasing dissolution time and increase in temperature. This research aims to assess the machinability of medium carbon low alloy DPS which was subjected to dual phase (F-B) treatment. Dual phase treatment is carried out by varying the intercritical temperatures from 750, 770 and 790 °C. The effect of both dual phase structure on machinability is studied and optimum tool life (Tₐ) along with surface roughness (Sₐ) values have been determined.

The machinability of these materials is also very important, particularly with respect to the martensite fraction. Optimum cutting parameters in machining should be determined for dual-phase steels with respect to the martensite fraction and the tool types. This knowledge would be very helpful for accelerating the machining process and improving the Tₐ and Sₐ with the lower power consumption, less usage of material and less amount of fluid consumption. Some of the authors compared dry condition machining with the wet condition machining operation using different cutting tools and they have suggested that carbide cutting tool gives longer Tₐ compared to other tools. Another author suggested that better Sₐ as well as optimum Tₐ can be achieved by using carbide cutting tools.

The effect of cutting variables on MRR and tool wear for EN8 steel has been investigated. High speed steels and carbide tip tools are widely used for cutting. Hardness, wear resistance, thermal stability and strength are the cutting variables that influence the efficiency of the tool. Cemented carbides are used due to their high hot hardness and wear resistance while low toughness being their main disadvantage. The wear resistance of EN-8 steel can be enhanced by using surface hardening techniques. The increase in speed, feed or depth of cut (DoC)leads to higher tool wear and higher the spindle speeds the higher the MRR studied the single response optimization of turning parameters for EN-8 steel to
optimize the $S_p$ and tool tip temperature in turning operations using single point carbide cutting tool. Optimum values of speed and depth of cut were obtained using L9 orthogonal array and ANOVA (Analysis of variance) was employed to analyze the effects of the process parameters during turning. Mathematical tools like Signal to noise ratio (S/N) and Variance was analyzed using Taguchi method to understand the effect of different machining parameters on $S_p$ and tool tip temperature values. Experimentation revealed that $S_p$ is directly proportional to increase in speed but inversely to increase in depth of cut and tool tip temperature is directly proportional to both speed and depth of cut. The effect of cutting parameters on the flank wear during CNC (with a maximum spindle speed of 4000 rpm) turning of EN8 steel has discussed. Three different types of tool inserts used are uncoated carbide insert (GRADE: TTS), uncoated carbide insert (GRADE: TTR) and coated carbide insert (GRADE: K10U). Flank wear behavior is little varied for different speeds and feeds and is a complex function of both the parameters. It was also observed that the coated type of tool insert K10U showed the minimum flank wear out of the three different types of tool inserts used and thus has the longest $T_w$ in these cutting conditions. In addition, it was observed that optimum conditions to get minimum flank wear are medium speed and medium feed rate\(^{14}\). The optimization of machining parameters like speed, feed and depth of cut for EN-8 steel with a tungsten carbide tip tool was discussed. Statistical analysis through Taguchi method is used to find the optimum range of speed, feed and depth of cut to minimize the surface roughness. First phase is the machining of the selected work piece and tools using conventional methods where time and final weight are noted while the second phase is the analysis of machined work pieces and tool. MRR and tool wear rate are calculated and SEM test helps in understanding the property of machined surface. Taguchi method is used as it allows us to modify the time factor and yet evaluate the influence of each factor and it allows us to experiment in limited number and predict the remaining permutations of factors. The optimized results showed that optimum speed is 450 rpm, feed is 0.110 mm/rev and depth of cut is 1.2 mm\(^{15}\). The optimization process will help to improve $S_p$ and optimum amount of material removal rate which increases the $T_w$\(^{16}\).

The influence of machining parameters like cutting speed, depth of cut and feed on EN-8 steel for MRR in multiple operations like turning, facing operations reported. Different experiments are conducted for the various experimental runs and the experimental results lead to the formulation of empirical equation, through which predicted value of MRR is calculated. Genetic algorithm is used to solve the empirical equation. The optimal speed value for MRR is 800 rpm while the optimum feed value is 0.1 mm/rev. The genetic algorithm also finds the best fitness value as 0.326107 g/sec and one can see that MRR is directly proportional to feed rate and spindle speed\(^{17}\). The detailed analysis of $S_p$ in dry machining of EN-8 steel was reported. Regression models are created for Ra, Rq, and Rz parameters of surface topology, which are important parameters from contact stiffness, fatigue strength and surface wear perspective. Taguchi method was used in the experiments, for the three factors at three levels. It is discovered that the percent errors are little for regression modes when contrasted with geometrical model. The results of the experiments show clearly that there is no significant difference in the $S_p$ in dry machining as compared to machining with a coolant\(^{18}\). In another study, optimization of the process parameters like speed, depth of cut and feed are obtained to achieve the better machinability for the material which can be used in industrial application\(^{19}\). Few authors have also reported about wet condition machining process. In this process, more amount of oil consumption helps to improve the specific energy consumption and helps in obtaining less friction between $T_w$ and the workpiece\(^{20}\).

However, not many reports are available regarding the machining behavior of ferrite-martensite DPS. As this material is being used in wide range of application, understanding its machining behavior would immensely helpful for the manufacturer. In this study, machinability in terms of $T_w$ and $S_p$ for the ferrite-martensite DPS is determined. Also, in order to get the optimum combination of $T_w$ and surface roughness, machining parameters are obtained.

2. Materials and Methods

2.1. AISI 1040 steel

Round samples of size 100 length and 20 mm dia were prepared from industrial steel of the chemical composition specified in Table 1. The intercritical heat treatments at 750, 770 and 790°C were carried out on these steel specimens to obtain three different martensite volume fractions. These temperatures were utilized and corresponded to low, medium and high martensite volume fractions (approximately 30, 50 and 80%) in the steel. In addition, the normalizing treatment at 900 °C was also performed for one group of specimens to achieve the better machinability for the material which can be used in industrial application. After finishing the thermal treatment procedures, the martensite volume fractions in the intercritically heat treated samples were checked using an image-processing computer program.

Taguchi method is a very powerful statistical tool. It involves selecting the parameters and the factors affecting these parameters. It identifies the levels of all the factors affecting the parameters and then forms an orthogonal array. This orthogonal array shows all the possible combinations of all the factors. Program behind this Taguchi tool analyses the data and gives us the optimum sets of combinations of

| Type of Steel | C   | Mn  | Si  | Cr  | Mo  | Ni  | Fe    |
|--------------|-----|-----|-----|-----|-----|-----|-------|
| AISI 1040    | 0.39| 0.72| 0.10| 0.03| 0.02| 0.02| Remainder |
Figure 1. Silicon carbide tool.
i.e., lower temperature (750 °C), speed (115 m/min) and depth of cut (0.2 mm) conditions show better T_L compared to higher temperature. But the selected feed is having least effect on the DPS.

3.3. Analysis of variance for surface roughness

ANOVA for S_R magnitude will describe the control factors significance on the S_R. At higher temperature, quantity of martensite is more that leads to lesser T_L due to increased hardness and strength. It is seen that temperature has maximum effect on S_R with 46.54% and 38.11% contribution on T_L due to increase in wt.% of martensite content and decrease in ferrite wt.%. Similarly speed also has 41.50% contribution on S_R and 31.14% on T_L. As the cutting speed increases T_L decreases and S_R increases. Feed has least contribution on

| Sl No | Temperature (°C) | Speed (m/min) | Feed (mm/rev) | DoC (mm) | T_L (s) | S_R (µm) |
|-------|-----------------|---------------|---------------|---------|--------|---------|
| 1     | 750             | 80            | 0.13          | 0.2     | 2098   | 4.07    |
| 2     | 750             | 80            | 0.13          | 0.2     | 2138   | 4.05    |
| 3     | 750             | 80            | 0.13          | 0.2     | 2145   | 4.00    |
| 4     | 750             | 115           | 0.15          | 0.4     | 1305   | 3.62    |
| 5     | 750             | 115           | 0.15          | 0.4     | 1301   | 3.56    |
| 6     | 750             | 115           | 0.15          | 0.4     | 1321   | 3.67    |
| 7     | 750             | 150           | 0.18          | 0.6     | 411    | 3.07    |
| 8     | 750             | 150           | 0.18          | 0.6     | 405    | 3.21    |
| 9     | 750             | 150           | 0.18          | 0.6     | 420    | 3.09    |
| 10    | 770             | 80            | 0.15          | 0.6     | 1041   | 4.02    |
| 11    | 770             | 80            | 0.15          | 0.6     | 1054   | 4.089   |
| 12    | 770             | 80            | 0.15          | 0.6     | 1059   | 4.07    |
| 13    | 770             | 115           | 0.18          | 0.2     | 1023   | 2.99    |
| 14    | 770             | 115           | 0.18          | 0.2     | 1046   | 2.98    |
| 15    | 770             | 115           | 0.18          | 0.2     | 1045   | 2.96    |
| 16    | 770             | 150           | 0.13          | 0.4     | 543    | 2.49    |
| 17    | 770             | 150           | 0.13          | 0.4     | 598    | 2.39    |
| 18    | 770             | 150           | 0.13          | 0.4     | 568    | 2.45    |
| 19    | 790             | 80            | 0.18          | 0.4     | 698    | 2.66    |
| 20    | 790             | 80            | 0.18          | 0.4     | 686    | 2.67    |
| 21    | 790             | 80            | 0.18          | 0.4     | 693    | 2.66    |
| 22    | 790             | 115           | 0.13          | 0.6     | 235    | 2.92    |
| 23    | 790             | 115           | 0.13          | 0.6     | 245    | 2.95    |
| 24    | 790             | 115           | 0.13          | 0.6     | 226    | 2.90    |
| 25    | 790             | 150           | 0.15          | 0.2     | 398    | 2.16    |
| 26    | 790             | 150           | 0.15          | 0.2     | 393    | 2.14    |
| 27    | 790             | 150           | 0.15          | 0.2     | 387    | 2.17    |
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T and S, whereas depth of cut has least contribution on S and moderate on T.

S is an important factor for machined components. Main effect plot (Figure 6) shows the effect of independent factors effect on the dependent factor (surface roughness). Temperature and speed are having highest contribution on the S of DPS. Feed and DoC have marginal effect on S (Table 4 and Figure 6). In a dual phase condition as the intercritical temperature increases from 750 to 790 °C which reduces the ferrite and increase the quantity of martensite. Ferrite is softer in nature and martensite is harder but combination of both leads to improve the machinability of the DPS. the weight percentage of dual phases, size and shape of individual phases quality and quantity of the DPS helps to improve the surface roughness. The increases the tetragonality of BCT martensite cell to form maximum distortion in the lattice and atomic cluster of martensite is which increases hardness of the martensite. For this reason, at lower critical temperature results shows lesser surface finish compare to higher intercritical temperature.

3.4. Error analysis for T and S of AISI 1040 F-M DPS

Statistical analysis is validated through regression equations. Difference between the actual and predicted results is shown as % Error.

Figures 7 and 8 show the error analysis for T and S respectively. It is observed that predicted and actual results are approximately same for all the test trials. Difference of predicted and actual results are minimal, and it confirms the R-Square values obtained for T and S. The experimental results recorded prove that regression equations obtained for this study may be used to predict T and S.

3.5. Optimization of process parameters for AISI 1040 F-M DPS

Optimization is carried out by using response surface optimization technique for all machining variables and temperatures. Optimization is performed to get better T and S of heat treated steel. Larger T and lower S are the requirement in machining. By combining both T and S better machinability can be achieved.

Figure 9 shows the detailed response optimization of T and S values. From the results, in order to obtain the optimum combination of T and S values RSM is used. Accordingly, values for different machining parameters are obtained. The composite desirability, D value of 0.9555 shows that the obtained optimized results have good fit. Optimum T and S have been observed at 770 °C temperature treated dual phase AISI1040 steel. Considering speed, feed and

Table 3. ANOVA for T

| Factors          | Degree of freedom | Seq sum of square | Adj MS     | P        | % Contribution |
|------------------|-------------------|------------------|------------|----------|----------------|
| Temperature (°C) | 2                 | 3199142          | 1599571    | <0.001   | 38.11          |
| Speed (m/min)   | 2                 | 3116934          | 1558467    | <0.001   | 31.14          |
| Feed (mm/rev)   | 2                 | 342628           | 171314     | <0.001   | 4.08           |
| DoC (mm)        | 2                 | 1730726          | 865363     | <0.001   | 20.62          |
| Error           | 18                | 1932             | 220        |          |                |
| Total           | 26                | 8393396          |            |          |                |

Table 4. ANOVA for S

| Factors          | Degree of freedom | Seq sum of square | Adj MS     | P        | % Contribution |
|------------------|-------------------|------------------|------------|----------|----------------|
| Temperature (°C) | 2                 | 5.0471           | 2.52356    | <0.001   | 46.54          |
| Speed (m/min)   | 2                 | 4.5004           | 2.25020    | <0.001   | 41.50          |
| Feed (mm/rev)   | 2                 | 0.5110           | 0.25550    | <0.001   | 4.71           |
| DoC (mm)        | 2                 | 0.5474           | 0.27371    | <0.001   | 5.05           |
| Error           | 18                | 0.2331           | 0.01327    |          |                |
| Total           | 26                | 10.84            |            |          |                |
4. Conclusion

Following conclusion are arrived after conducting machining tests on DPS.

1. Better $T_L$ was obtained for the DPS, heat treated at the lower intercritical temperature of 750 °C. Misconstrue shows the formation of dual phase depending on the intercritical temperature.
2. Experiential and statistical results revealed that speed and depth of cut are major contribution factors on $T_L$ and $S_R$.
3. Increase in the cutting speed has resulted in the reduction of $T_L$. Cutting speed has also major contribution on the variation of surface roughness.
4. With increase in depth of cut, $T_L$ decreases due to enhancement in tool wear as the contact area between tool and work material increases.
5. Increase in the cutting speed has resulted in the reduction of roughness value and smooth surface is obtained at higher speeds with minimum depth of cut.
6. The effect of the cutting speed and depth of cut on $T_L$ is more pronounced, than the effect of feed.
7. RSM and its validation results confirm optimum $T_L$ of 1492 seconds and 3.11 microns as $S_R$ for F-M dual phase. The composite desirability $D$ value of 0.955 (near to 1) shows that the obtained optimized results have good fit at intercritical temperature of 770 °C.

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