Turned AISI 4340 Heat-Treated Steel Surface Quality Investigations in Dry and MQL Cooling Conditions

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Abstract: Heat treatment of machine components such as Annealing, normalizing, hardening, case hardening and other surface treatments have given better endurance to static and dynamic loads and stresses for many service applications. Most of the components are heat treated after machining once major dimensional controls are met. However, after heat treatment, it was observed the dimensional inaccuracies such as actual dimensions values, surface quality deterioration due to scale formation and material combinations with surrounding media at elevated temperatures attempts to recheck the errors and dimensional variations in the components. Machining after heat treatment also is necessary and is practiced and there arises problems of different chemistry and physical behavior of tool and material machining conditions. In order to know the effects of the heat treatment on machining, an attempt is made to study the variations in the process using design of experiment (DOE) approach taking surface roughness parameter as response.

Keywords: MQL, Turning, Steel 4340, DOE

1. INTRODUCTION

Turning steels with optimum cutting conditions of Cutting Speeds, feeds and depth of cuts are generally the scope of study in classical machining theories, but since with the applications of cooling systems for reduction of cutting temperatures and material characteristics of work-piece due to different hardness levels tend to disrupt the optimum values and the scheme of study hence requires to work for schematic arrangement of cooling system in turning, to link all facilities and accessories such as tooling and draw valid conclusions on the same. Following is the schematic representation of an arrangement of turning operation as follows:

![Figure 1. Turning Operation with Coolant Input (MQL)](image-url)
## 2. LITERATURE REVIEWS

| Author(Year), Reference | Description |
|-------------------------|-------------|
| Shaikh, V. A., & Boubekri, N. (2020). [1] | A review of metal working fluids (MWFs) based on vegetable oils w.r.t mineral oils in turning, drilling and milling operations were studied in detail. Comparison of different cutting conditions like machining parameters, cooling and lubrication, mix ratios were done with response outputs like surface roughness, tool wear measurements, cutting temperatures, cutting forces and heat transfer coefficients. It was concluded that a good number of vegetable oils are in existence today that can replace part or wholly the burden and detrimental effects of mineral oils in the machining sector. Proper selection of MWFs depends majorly on the different cutting conditions, work material, tool used and method of coolant application and preparation of MWFs. |
| Rabin Kumar Das et al. (2018) [2] | Coated Carbide Inserts were experimented in different cooling conditions for heat treated work-pieces yielding hardness values of 50±1HRC. PVD coated carbide inserts provide stable machining with less chances of tool sudden failures and chipping out. MQL gave best results as compared to dry cutting in terms of tool wear, surface finish. Machining parameters like cutting speed and feed had profound effect on response measurements. |
| Masoudi, S. et al. (2017) [3] | Three factors such as Nozzle orientation, Work hardness (heat treated) and tool type taking 4 levels and response measures like surface roughness, cutting forces, tool wear were studied. Turning operation were performed in MQL environments only. Efficiency of MQL is indicative to the fact that chip curl is better. Implementation of 2 nozzle system has a superior effect on responses. Carbide tools outperformed HSS tools. The values of surface roughness is found to reduce with increasing hardness values of work material. |
| R Suresh et al. (2013) [4] | Machinability of harder steel material was studied. Hard Machining requires a negative rake tool with low feeds and depth of cuts. Feed rates are the major influential factors in hard turning process for surface finish. Tool wear has detrimental effects such as material changes, surface roughness and so, tool selection is a major concern for hard machining. A careful study of the microstructure analysis has been made to understand the hard turning issues with varying parameter levels in turning operation. |
| Ramandeep Singh Johal et al. (2017) [5] | Finish turning of AISI 4340 steel using Soya-bean oil (MQL cooling) was studies for tool life analysis, surface roughness and machining time as responses. It was concluded that Surface speeds have more influence followed by feed rates and proved that MQL outperformed better than Dry cutting conditions. |
| M VeeraBhadra Rao et al. (2019) [6] | A review of nano-materials such as Graphene, MoS2 and Al2O3 mixed in different vegetable oils was studied. Ultra-sonication times higher than one hour leads to better stability MWFs. Hybrid nano-material fluid mixtures can give blended benefits for lowering friction, reducing temperatures and better cooling. Viscosity and temperature of nano-fluids also have an effect on success of high machinability performance index. |
| M VeeraBhadra Rao et al. (2019) [7] | EN24 steels were turned using uncoated carbide inserts under mist cooling using coconut oils and to analyse tool wear pattern, surface finish and chip thickness values. Mist cooling outperformed Dry and flooded lubrication methods in terms of lower flank wear of tools and surface finish of turned components. Feed rates increase surface roughness values as it is increased. |
and vice-versa. Flank wear is affected greatly by the cooling conditions as indicated by ANOVA analysis. Chip thickness are found to be lesser and bright colour in mist lubrication and chips are safer to handle due to blunt edges of chip.

Rao M.V.B et al. (2018) [8] Safer vegetable oils for machining such as Coconut oil, canola oil, sesame oil, etc can be used instead of mineral oils to exhibit bio-degradability and hence safety to environment. It was indicated that nano-materials added in these veg.oils with proper mix (0.2 to 5% wt) by two-step method like ultrasonication can enhance thermal conductivity of the cutting oils. The size, shape, material and mix method for nano-fluid plays a major role for success of machining. It was also indicated that a special chemical like Sodium Dodecyl Benzene Sulphonate SDBS can enhance stability of nano-fluids. Semi-Solid lubricants with the nano-materials also can be best possible versions for machining steels and its merits & demerits can be compared on grounds of safety and health concerns of ecosystem and workers.

VeeraBhadra Rao M. et al. (2018) [9] Other than the above nano-fluids and MQL advantages, reviews related to use of Infra-red Camera for temperature measurements, CFD software simulations for better analysis of responses and knowledge of ANSYS may help discover hidden potential of research in the field of machining.

3. RESEARCH METHODOLOGY

AISI 4340 steel material of 30 mm diameter and length 200 mm was selected for study. The work-pieces were divided into three batches, one batch was not heat treated. Other batch was annealed and final batch was hardened. These test pieces were measured for material hardness in Brinell hardness tester according to ASTM E-10 standards. In turning of these three batch of work-pieces, Kirloskar Lathe was selected for machining studies and using P type carbide insert (Uncoated) of CNMG120408 geometry. Depth of cut is maintained constant throughout the study of 0.5 mm. Minimum Quantity Lubrication (MQL) cooling is offered by Kenco Mist Lubrication System fitted with Lathe machine and coolant - Coconut Oil is made to pass through the nozzle on to the tool chip interface. Nozzle was kept 5 mm away from the tool-chip interface with a flow rate of 60 ml/hr. Surface Roughness (Ra) was measured in each experimental runs and the results were analyzed by MINITAB software.

3.1 Work-piece Hardness values

Hardness for non-heat treated condition work-pieces was found to be 184 HBW, for Hardening condition was 328 HBW, for annealed condition was 219 HBW respectively.

4. EXPERIMENTAL DESIGN

The Experimentation Design Variables are shown in table 1

| Machining Parameter                  | Level 1 | Level 2 | Level 3 |
|-------------------------------------|---------|---------|---------|
| Machining Condition                 | Dry Cut | MQL Assisted | --     |
| Heat Treatment Process on Work-piece| Not Heat Treated | Annealing | Hardening |
| Cutting speed (m/min)               | 70      | 90      | 150     |
| Feed rate (mm/rev)                  | 0.18    | 0.25    | 0.315   |
5. EXPERIMENTAL RESULTS

Surface roughness values were noted at all experimental runs as follows:

Table 2. Surface Roughness Values in Turning AISI 4340 steel

| Expt run | Condition      | Heat Treatment Process on Work-piece | Cutting speed (m/min) | Feed (mm/rev) | Surface roughness (µm) |
|----------|----------------|-------------------------------------|-----------------------|---------------|------------------------|
| 1        | Dry Cut (1)    | Not heat-treated (1)                | 70(1)                 | 0.18(1)       | 4.02                   |
| 2        | Dry Cut (1)    | Not heat-treated (1)                | 90(2)                 | 0.25(2)       | 6.5                    |
| 3        | Dry Cut (1)    | Not heat-treated (1)                | 150(3)                | 0.315(3)      | 7.12                   |
| 4        | Dry Cut (1)    | Annealing (2)                       | 70(1)                 | 0.25(2)       | 5.2                    |
| 5        | Dry Cut (1)    | Annealing (2)                       | 90(2)                 | 0.315(3)      | 3.01                   |
| 6        | Dry Cut (1)    | Annealing (2)                       | 150(3)                | 0.18(1)       | 2.1                    |
| 7        | Dry Cut (1)    | Hardening (3)                       | 70(1)                 | 0.315(3)      | 2.41                   |
| 8        | Dry Cut (1)    | Hardening (3)                       | 90(2)                 | 0.18(1)       | 3.12                   |
| 9        | Dry Cut (1)    | Hardening (3)                       | 150(3)                | 0.25(2)       | 2.51                   |
| 10       | MQL Assisted (2)| Not heat-treated (1)               | 70(1)                 | 0.18(1)       | 2.8                    |
| 11       | MQL Assisted (2)| Not heat-treated (1)               | 90(2)                 | 0.25(2)       | 2.3                    |
| 12       | MQL Assisted (2)| Not heat-treated (1)               | 150(3)                | 0.315(3)      | 2.61                   |
| 13       | MQL Assisted (2)| Annealing (2)                       | 70(1)                 | 0.25(2)       | 2.65                   |
| 14       | MQL Assisted (2)| Annealing (2)                       | 90(2)                 | 0.315(3)      | 2.63                   |
| 15       | MQL Assisted (2)| Annealing (2)                       | 150(3)                | 0.18(1)       | 3.28                   |
| 16       | MQL Assisted (2)| Hardening (3)                       | 70(1)                 | 0.315(3)      | 3.63                   |
| 17       | MQL Assisted (2)| Hardening (3)                       | 90(2)                 | 0.18(1)       | 2.1                    |
| 18       | MQL Assisted (2)| Hardening (3)                       | 150(3)                | 0.25(2)       | 2.77                   |

5.1 Analysis of Main Factors and Interactions

Data from Table 2 is used for analysis using Minitab software and the graphs are as shown in Figure 1, Figure 2 and Figure 3 respectively.
Figure 2. Graphs showing Means of S.R (Surface Roughness) of factors at different levels

Figure 2 graph (Mean of S.R) and Figure 3 graph (Mean of SN ratios) shows exact replica but reverse order, but the both give same results. In case of Figure 2 graph, Machining condition at MQL condition (Level 2), Heat Treatment process at Level 3 (Hardening process), Cutting Speed at Level 2 (90 m/min) and feed rate at Level 1 (0.18 mm/rev) are the optimum combination. Same as seen in SN ratio graphs, where we consider the highest values of SN ratios in each factor graphs. So, we get the same combinations as similar to Figure 2, i.e. Machining condition at MQL condition (Level 2), Heat Treatment process at Level 3 (Hardening process), Cutting Speed at Level 2 (90 m/min) and feed rate at Level 1 (0.18 mm/rev).

Figure 3. Graphs showing Means of SN ratios (Signal to Noise ratios) of factors at different levels

This proves the fact that MQL cooling is better than Dry lubrication, possibly due to less tool damage and smooth cutting thereby enabling a bright chip cut at the interface of tool-work. The temperature gradients are lessened due to MQL cooling which enhances a ductile and long chip curl and less chip and work surface hardening during cutting. Heat treatment graphs shows that Hardening process yields better surface finish than non heat treated and annealed work-pieces. Amount of hardness provided is adequately practiced to attain a proper chip cutting w.r.t work surface thereby avoiding deterioration of work surface. Annealing and non heat treated work-pieces, due to its ductile nature, can be thought of tool nose digging into the work surface and thereby chip carried away might have effect on the work surface, this can be avoided and made workable if geometry of tool nose radius and other features of tool can be considered. Since tool geometry is held constant, annealing and untreated work-pieces showed higher surface roughness values.
Most of the cutting speeds in turning operations as per ASME standards work efficiently at range of 80-120 m/min for medium and high carbon steels, as per our experimental results and analysis, this proves that 90 m/min as surface speed is optimum for carrying out machining.

Lower feed rates of 0.18 mm/revolutions ensures better surface finish, as feed rates are increased, the surface finish deteriorates. Lesser feed rates ensures less deformation of material as chip material, less thermal effects and longer tool life. Though time taken for machining will increase with lesser feed rates, smooth surface finish on the work surface can be achievable at lower feed rates.

Referring to Figure 4, as per the conventions of Interaction plots, if parallelism of lines exist in a graph between two or more factors, then no interaction occurs and vice-versa. The more the non-parallel lines are, the strength of the interaction effects of factors are subsequently larger and higher. As from the figure 4, higher interactions are found in graph 3 - a, c, d, e, f, h, i, j, k, l which proves that factor interactions have a role play in the response characteristics which can be studied by use of ANOVA table and its significance as future study process.

6. CONCLUSIONS

1. Lower feed rates in machining, surface speeds of 100 m/min are common machining parameters which gives optimum surface roughness values.
2. Requirement of MQL coolant system for ensuring coolant flow, and minimizing excessive fluid waste can be employed which can promote to practicing green manufacturing.
3. Material hardness can contribute to surface finish qualities, however higher hardness levels are not worked with, but soft ductile materials machining tend to produce higher surface roughness values, with a compromise in tool material as there will be loss of tool due to erosion and wear off when machining harder materials. This may require further investigation on better tools either coated technologies or study of geometry (nose radius) etc. Certain amount of material hardness by using heat treatment can be incorporated to have an effect on surface quality.
4. ANOVA analysis can be used to understand the percentage contribution of each factors and its interactions.
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