Comparative Study of Carbide Tools in Turning of High-Chrome White Cast Iron using Hard Turning Methods

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Abstract: Thermally enhanced machining (TEM) is a new practice in hard turning of hard materials like White cast iron, Inconel 718 steels etc. Addition of preheating before shear zone improves the elasticity of the material. Before this, Industries invested more capital on toolings and robust machineries/equipments, also it demanded high cost diamond, Cubic boran nitride (CBN) and poly CBN (pCBN) tools. This research paper mainly focusses on the comparative study of machinability characteristics like machining forces and surface roughness of a high hard High chrome white cast iron (HCWCI) when turning with and without the addition preheat using multilayer hard coated carbide (TiC/TiCN/Al₂O₃). Taguchi technique were used to carry out the experimental work. The experimental and theoretical investigations are done in different phases in order to derive some of the useful process responses like machining forces, surface roughness etc, and to prove Oxy-LPG aided TEM most appropriate methodology to cut HCWCI. Furthermore derived the suitable conditions at which the coated carbide tools perform better. Hence comparative studies of each process responses are required to arrive to the reasonable conclusions.

Keywords: High Chrome White Cast Iron (HCWCI), Thermally enhanced machining (TEM), Taguchi method, Multi coated Carbide insert

1. Introduction

The demand for hard materials like Chromium white cast irons, Tool steels, High manganese steels, Inconel 718 steels, Nickel chromium steels etc has increased significantly in the field of Mining, Agricultural, Aerospace, Defense and Process Industries [1-4]. Machining of such materials has always been a tough job, so Industries opt for casting process to shaping of the product. However, drastic developments in the tooling bring back metal cutting methods like high-speed machining [2] and thermally enhanced machining (TEM) [1]. In hard turning, frictional heat softens the work material by increasing the cutting speed or adding external heat to the tool-work interface [4,5]. Interestingly TEM method overrides the conventional high-speed machining and brings economical reprieve to the Industries [1,4].

In their research work, Ravi AM et. al (2014) conducted series of experimentations to optimize the machinability characteristics of high hard HCWCI with and without addition of preheat using CBN
and multilayer coated carbide tools. And stated that, the favourable properties of CBN always be a better choice in hard turning of HCWCI, however the introduction of coating techniques brings back the hard carbide tools in-line with the CBN tools.

Since, the local heat added to the tool-work interface causes severe tool wear on the flank and rake faces of the tool, but, setting up of optimum cutting conditions made TEM an effective tool in hard turning of HCWCI [1-4,7,8]. The main objective of this research paper is to compare the performances of carbide tools at different cutting conditions in order to optimize the process parameters for the benefit of the Industry in manufacturing components for various applications.

2. Experimental setup

The material chosen for this experimentation was sand blasted air quenched HCWCI made in the form round bars having dimensions; 50mm diameter and 400mm long. The work material was an abrasion wear resistant hard material, and its chemical compositions are; 2.7%C, 0.7%Si, 0.66%Mn, 0.068%S, 0.7%P, 0.5%Cu, 27.93%Cr and 0.5%Mo. Some of the important properties HCWCI are; 1260°C Melting point, 7.7gm/cc Density, 13W/mk Thermal conductivity, 541 BHN hardness. The tooling’s used are; Multilayer hard coated carbide (TiC/TiCN/Al₂O₃) inserts, and indexable tool holder (Mitsubishi make, PCLNR/L 2525MO9 type, insert seating geometry angles; normal rake angle -6°, back rake angle -6°, clearance angle 6° and angle of lap 95°) to mount the insert[1,3,6,10].

![Figure 1. Experimental set up for TEM process.](image)

Here Oxy-acetylene gas was used as the heat source to generate the flame, and the mixture was controlled with the help of flow control valves. A non-contact type thermal sensor was used to set surface temperatures. Figure 1 illustrate the set up for hot machining process where preheat (Flame) added to the work before metal cutting process.

| Sl. No. | Control factors     | Levels | Units  |
|--------|---------------------|--------|--------|
| a      | Cutting speed, S    | I 55   | II 88  | III 132 | m/min |
| b      | Depth of cut, d     | I 0.1  | II 0.2 | III 0.3 | mm    |
| c      | Feed rate, f        | I 0.096| II 0.124| III 0.179| mm/rev|
| d      | Surface Temperature, Ts | I 250 | II 350 | III 450 | °C    |

3. Results and discussions

Adopted Taguchi’s procedures to carryout experimentations on HCWCI using carbide inserts with and without the addition of preheat [1,3,10]. Table 1 shows the range of cutting parameters selected for both the experimentations. For each experimental trial a new cutting edge was used, and the experiments were repeated thrice at each condition to keep the experimental error to a minimum value.
During experimentation a special care was taken to identify the crack formation on the surface of the work after machining using flaw detector (Orion model, Type-115D). Cutting forces ($F_t$, $F_c$, and $F_f$) were measured using Piezo-electric lathe tool dynamometer (Kistler model 9712B500). The surface roughness of the turned part was measured using Surtronic-10 Taylor Hubson surface roughness measuring instrument. The cutting forces and surface measurements were recorded separately for hard turning and TEM process, and the percentage differences are tabulated in Tables 2 and 3.

| Trail Nos | Control Parameters | Percentage differences |
|-----------|--------------------|------------------------|
|           | $S$, m/min | $d$, mm | $f$, mm/rev | $T_b$, °C | $F_t$, N | $F_c$, N | $F_f$, N |
| 1         | 55         | 0.1     | 0.096       | 200       | -29      | -26      | 29       |
| 2         | 55         | 0.1     | 0.124       | 325       | -73      | -19      | 34       |
| 3         | 55         | 0.1     | 0.179       | 450       | -55      | -28      | 30       |
| 4         | 55         | 0.2     | 0.096       | 325       | 28       | 25       | 63       |
| 5         | 55         | 0.2     | 0.124       | 450       | 30       | 25       | 63       |
| 6         | 55         | 0.2     | 0.179       | 200       | 29       | 27       | 68       |
| 7         | 55         | 0.3     | 0.096       | 450       | -53      | 27       | 71       |
| 8         | 55         | 0.3     | 0.124       | 200       | -70      | 31       | 74       |
| 9         | 55         | 0.3     | 0.179       | 325       | -82      | 28       | 71       |
| 10        | 88         | 0.1     | 0.096       | 200       | -40      | 45       | -38      |
| 11        | 88         | 0.1     | 0.124       | 325       | -61      | 39       | -60      |
| 12        | 88         | 0.1     | 0.179       | 450       | -37      | 38       | -57      |
| 13        | 88         | 0.2     | 0.096       | 325       | -50      | 37       | 53       |
| 14        | 88         | 0.2     | 0.124       | 450       | -34      | 37       | 48       |
| 15        | 88         | 0.2     | 0.179       | 200       | -53      | 34       | 48       |
| 16        | 88         | 0.3     | 0.096       | 450       | -41      | -20      | -8       |
| 17        | 88         | 0.3     | 0.124       | 200       | -33      | -14      | -8       |
| 18        | 88         | 0.3     | 0.179       | 325       | -30      | -11      | 6        |
| 19        | 132        | 0.1     | 0.096       | 200       | -36      | 48       | 35       |
| 20        | 132        | 0.1     | 0.124       | 325       | -9       | 53       | 33       |
| 21        | 132        | 0.1     | 0.179       | 450       | -62      | 44       | 28       |
| 22        | 132        | 0.2     | 0.096       | 325       | -37      | 48       | -15      |
| 23        | 132        | 0.2     | 0.124       | 450       | -46      | 49       | -5       |
| 24        | 132        | 0.2     | 0.179       | 200       | -67      | 46       | -8       |
| 25        | 132        | 0.3     | 0.096       | 450       | -66      | 24       | 28       |
| 26        | 132        | 0.3     | 0.124       | 200       | -59      | 24       | 23       |
| 27        | 132        | 0.3     | 0.179       | 325       | -29      | 30       | 16       |

| Total     | -1064      | 642      | 620       |
| Average   | -39        | 24       | 23        |
3.1. Comparison of cutting forces

It is known that the cutting forces generated during machining of HCWCI are; thrust force, $F_t$, main cutting force, $F_c$, and feed force $F_f$. In this research work all the experiments were conducted keeping the angle of lap as 75° for better angle of contact against the workpiece [1,3,6].

3.1.1. Thrust force analysis

Thrust force is one of the components of the machining force acting along the radial direction of the workpiece during machining. Figure 2 shows the comparison of Thrust force at different cutting conditions during machining of HCWCI using coated carbide tools. The research analysis reveals, thrust force measures high, especially in hard turning [2], but behaved differently in TEM process[1,2,4]. The reason might be due to angle of lap, tool nose radius and cutting parameters[1,4]. Also the contribution of each control factors on the thrust force, in which depth of cut has significant contribution to the thrust force followed by surface temperature. An increase in depth of cut increases the thrust force due to increased tool-work contact length, hence more frictional resistance to shear the metal [1,4]. The broad nose radius of the tool having contact only at the radius rather than cutting edge, especially at the lower depths of cut. Obviously it generates more amount of thrust force [8,11]. Kainth et. al (1990) identified the same during their experiments using CBN tools. Also, the formation of the flank and crater wear has more influences on the cutting forces, predominantly the thrust force [7].

![Figure 2. Comparison of Thrust force at different cutting conditions during machining of HCWCI using coated carbide tools.](image)

3.1.2. Main cutting force analysis

The study reveals, in hard turning the main cutting force is the primary force acting along the z-direction (downward). However, its magnitude depends on the hardness of the workpiece, tool geometry and cutting parameters [1,4,6]. Also cutting speed has significant contribution to the cutting force followed by surface temperature. It was observed during the experimentations that, the main cutting force increases as the feed rate or depth of cut increases, on the other hand, decreases as the workpiece surface temperature increases due to softening of the workpiece [1,4]. At a higher shear zone temperature the shear strength of the workpiece declines and improves the volume of metal removal [4]. The increase in feed rate or depth of cut induces large volume of cut metal in a same unit of time. As and when the tool advances, the tool-work contact length increases which forms a longer shear front bonds around the primary shear zone (both plastic and elastic compression). The influences of these may improve the heat conduction at the shear zone [11,12]. When the temperature available at the shear zone is higher, the primary carbides along with eutectic carbides in a matrix of austenite
transformed to free secondary carbides (M₇C₃) as a result the carbon content of the matrix decreases [4]. Further increase of the surface temperature decreases the bulk hardness and microhardness of the workpiece [1], hence, lower cutting forces in TEM of HCWCI can be understood. This phenomenon looks similar to the hard turning experimental studies.

Figure 3 shows the comparison of Main cutting force at different cutting conditions during machining of HCWCI using coated carbide tools. The main cutting forces have lesser value in heat assisted trails compared to hard turning for all run over trails.

For the set values of feed rate and surface temperature, the cutting force increases as the depth of cut increases and decrease as the cutting speed increases. This indicates the sufficient amount heat generation at the primary shear zone to soften the metal [1,4]. Interestingly, as the feed rate increases main cutting force decreases, this is due to sufficient amount of heat transfer to the base metal during machining [4].

3.1.3. Feed force analysis

The feed force is the another important cutting force identified in hard turning and TEM process, but it is smaller in value compared to other forces. Figure 4 shows the comparative study of feed force at different cutting conditions during machining of HCWCI using coated carbide tools. It is understood from the characteristics curve that the feed force obtained during turning with or without the preheat have almost similar values. The experimental observations reveal that increase of feed force was due to insufficient heat transfer to the work base metal, and larger tool-work contact length at the shear zone. In their remarks Ravi AM et. al (2014) arrived to the same conclusion when doing experiments with coated carbides. In TEM process, the feed force decreases when surface temperature increases for constant feed rate and depth of cut. In an another case, for the set values of surface temperature and feed rate, the feed force increases as the cutting speed increases, interestingly, depth of cut has a considerable influence on the feed force.

3.2. Surface roughness

It is interesting to watch the performance of hard-coated carbide against CBN tool, since the tool newly introduced to turn the HCWCI. Table 3 shows the comparison of surface roughness of HCWCI at different cutting parameters and surface temperatures. The characteristic curves of the surface roughness shown in Figure 5 describe the behavior of the workpiece at different cutting conditions, and their trend looks similar. Among them, the curve at 315°C has the lowest surface roughness.
compared to the curves at 200 and 450°C. At higher surface temperatures, there might be chances of formation of BUE on the tool rake face due to which the cutting area enlarges which results in improper shearing of the metal [4,6].

Also the results confirm that, addition of preheat reduces the surface roughness up to 33.65%, except the roughness obtained at low depth of cut (\(d=0.1\)mm) with higher cutting speed (\(S=132\)m/min). The reason might be due to excess of heat absorbed by the top layer of the workpiece when exposed to the flame, also, the depth of heat penetration decreases as the depth of cut increases [4]. In addition, the broad tool nose radius of the tool has highest contact with the work at its nose radius for lower depths of cut. Hence, roughness of the workpiece is high at these conditions [1,7,8]. At higher cutting speeds, the time for heat conduction to the required depths is not available and so machined surface tends to approach that without heat assistance.

**Figure 4.** Comparison of feed force at different cutting conditions; during machining of HCWCI using coated carbide tools.

**Figure 5.** Comparisons of surface roughness of the workpiece at different surface temperature when turning HCWCI using coated carbide tool.
Table 3. Comparison of surface roughness of HCWCI at different surface temperatures.

| Trail Nos | Control Parameters | $R_s$ (µm) at different $T_s$ (°C) |
|-----------|--------------------|----------------------------------|
|           | $S$, m/min | $d$, mm | $f$, mm/rev | 32°C | 200°C | 315°C | 450°C |
| 1         | 55        | 0.1     | 0.096       | 0.192 | 0.186 | 0.178 | 0.150 |
| 2         | 55        | 0.1     | 0.124       | 0.172 | 0.178 | 0.169 | 0.173 |
| 3         | 55        | 0.1     | 0.179       | 0.152 | 0.149 | 0.108 | 0.134 |
| 4         | 55        | 0.2     | 0.096       | 0.183 | 0.179 | 0.179 | 0.161 |
| 5         | 55        | 0.2     | 0.124       | 0.202 | 0.219 | 0.200 | 0.205 |
| 6         | 55        | 0.2     | 0.179       | 0.209 | 0.219 | 0.204 | 0.209 |
| 7         | 55        | 0.3     | 0.096       | 0.421 | 0.346 | 0.317 | 0.319 |
| 8         | 55        | 0.3     | 0.124       | 0.425 | 0.399 | 0.393 | 0.387 |
| 9         | 55        | 0.3     | 0.179       | 0.420 | 0.396 | 0.387 | 0.299 |
| 10        | 88        | 0.1     | 0.096       | 0.170 | 0.178 | 0.176 | 0.158 |
| 11        | 88        | 0.1     | 0.124       | 0.181 | 0.176 | 0.161 | 0.170 |
| 12        | 88        | 0.1     | 0.179       | 0.151 | 0.146 | 0.125 | 0.137 |
| 13        | 88        | 0.2     | 0.096       | 0.401 | 0.396 | 0.274 | 0.385 |
| 14        | 88        | 0.2     | 0.124       | 0.400 | 0.400 | 0.295 | 0.323 |
| 15        | 88        | 0.2     | 0.179       | 0.396 | 0.392 | 0.321 | 0.367 |
| 16        | 88        | 0.3     | 0.096       | 0.148 | 0.311 | 0.152 | 0.233 |
| 17        | 88        | 0.3     | 0.124       | 0.151 | 0.306 | 0.160 | 0.230 |
| 18        | 88        | 0.3     | 0.179       | 0.162 | 0.326 | 0.169 | 0.220 |
| 19        | 132       | 0.1     | 0.096       | 0.381 | 0.378 | 0.371 | 0.392 |
| 20        | 132       | 0.1     | 0.124       | 0.374 | 0.370 | 0.346 | 0.392 |
| 21        | 132       | 0.1     | 0.179       | 0.358 | 0.388 | 0.353 | 0.394 |
| 22        | 132       | 0.2     | 0.096       | 0.163 | 0.176 | 0.161 | 0.177 |
| 23        | 132       | 0.2     | 0.124       | 0.210 | 0.163 | 0.163 | 0.214 |
| 24        | 132       | 0.2     | 0.179       | 0.193 | 0.224 | 0.214 | 0.190 |
| 25        | 132       | 0.3     | 0.096       | 0.290 | 0.201 | 0.167 | 0.294 |
| 26        | 132       | 0.3     | 0.124       | 0.198 | 0.220 | 0.195 | 0.299 |
| 27        | 132       | 0.3     | 0.179       | 0.230 | 0.297 | 0.226 | 0.299 |

4. Conclusion

For the set control factors, thrust forces generated in preheat condition appears to be more than that of no preheat conditions. However, there is a considerable decrement in the main cutting force (23.77% (average of the run order)) and feed forces (22.96%). In both the cases, the work metal receives adequate amount of cutting temperature for the set control parameters. The surface roughness of the workpiece at 315°C surface temperature has the lowest surface roughness compared to 200 and 450°C temperatures. At higher surface temperatures, chances of formation of BUE on the tool rake face are more due to which the cutting area enlarges as a result improper shearing of the metal. Finally, the comparative study reveals that thermally enhanced machining is better than hard turning where no preheat added to the process.
5. References

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