ABSTRACT
Results in literature show microstructural changes in the cryogenically treated high speed steel (HSS) tool materials that can influence tool lives and productivity significantly. However, the real machining performance of cryogenically treated HSS tools in actual turning process has not been reported in any candidly accessible study. In order to understand the effect of cryogenic treatment on HSS tools, a comparative investigation on machining performance of cryogenically treated AISI M2 HSS tools in orthogonal turning has been carried out in this study. The commercially available square shaped AISI M2 HSS bits were procured and grinded on tool and cutter grinder to obtain tool signature as per IS:3019-1973. Two groups of tools thus obtained were subjected to cryogenic treatment at two levels of −110 °C (shallow treatment) and −196 °C (deep treatment) independently in addition to traditional heat treatment and then the turning tests were executed in accordance to the International Standard Organization, ISO: 3685-1993. The criterion selected for determining the turning performance was based on the maximum tool flank wear (0.6 mm). The results showed that cryogenically treated AISI M2 HSS tools performed significantly better and the benefit achieved was considerably more in deep cryogenically treated tools as compared to shallow cryogenically treated tools.


1. INTRODUCTION
Numerous cutting tools have been developed continuously since the first cutting tool material suitable for use in metal cutting, carbon steel, was developed a century ago[1]. The first tungsten rich alloy that was formally classified as high speed steel (HSS) is known by the AISI designation T1, which was introduced in 1910 [2]. Although molybdenum rich high speed steels such as AISI M1 have been used since the 1930s, shortfalls and hence high costs of raw materials during World War II spurred the development of alloy designs with molybdenum being substituted for tungsten to produce cheaper steel. The developments in molybdenum rich HSS made them on par with and in certain cases better than tungsten rich HSS. This started with the use of M2 steel instead of T1 steel [3]. HSS is fairly well used in the industry particularly in small scale industries to date. The main applications of HSS tools are for drills, taps, milling cutters, broaches and also bits where the economical cutting speed is too low to think about carbide tools [4].

The life of HSS cutting tools plays a major role in increasing productivity and consequently is an important economic factor. Along with the ideal mishmash of alloying elements, a common approach used in the past to increase the life of HSS cutting tools has been to heat treat tool materials, which provides greater control over the range of properties such as excellent hardness and wear resistance allied to good toughness. One of the major problems associated with the conventional heat treatment of these steels is the content of retained austenite, which is soft, unstable at low temperature and transforms into brittle martensite during service. Transformation of austenite to martensite causes approximately 4% volume expansion, which results in distortion of the cutting tools. Thus subzero treatment is used for minimizing the amount of retained austenite in HSS tool materials. Cryogenic treatment, a supplementary subzero treatment to conventional heat treatment process, has been around for many years but is truly in its infancy when compared to heat-treating. Cryogenic treatment is the process of submitting a material to subzero temperatures (below 0 °C) in order to enhance the service life through morphological changes that occurs during treatment. In recent years, many small businesses have been set up to cryogenically treat finished HSS cutting tools claiming significant improvements on their wear resistance. However, scientific research on performance of cryogenically treated HSS tools in actual machining has been spotty, and only a few academic papers have been published especially on M2 HSS. The results can be surprisingly good, depending on the application as some reports claim 92–817% increases in tool lives after they have being treated at −196 °C [5].

Cryogenic treatment, the discipline upon which the present study is based, can be considered a recent development [6-13]. Enhancement of wear resistance of tool steels by cryogenic treatment has been cited in several studies [11, 14]. However, the available literature on the metallurgical changes conferred by cryogenic treatment lacks scientific understanding; also the contradictory results encountered lead to misunderstanding the practical application of cryogenic treatment [14-18]. Some investigators argue that the improvement of wear resistance occurs solitary due to transformation of retained austenite to martensite [6, 8, 10]. But, this phenomenon is a common characteristic to both the cold treatment and the cryogenic treatment, and thus the significant enhancement of wear resistance of tool steels by cryogenic treatment vis-à-vis cold treatment cannot be solely attributed to the conversion of retained austenite to martensite [7, 9, 18-21]. Many investigators indicate that the refinement of secondary carbides is the major cause for the improvement in wear resistance by cryogenic treatment [1-3, 8, 10, 20, 21]; but this opinion lacks appropriate experimental evidences [1, 8, 10, 20]. A few researchers have studied the effect of cryogenic treatment on cutting tool steels but no study has been found on the performance of cryogenically treated HSS tools in actual machining conditions. Gulyaev
cryogenic treatment was reduced further to −196 °C, [17] inferred that the improved wear resistance of Fe-1.4Cr-1C bearing steel by cryogenic treatment was due to constructive distribution of carbide rather than by transformation of retained austenite to martensite. Mohanlal et al. [20] did machining tests to study the effect of cryogenic treatment on different steels and obtained nearly 110%, 87%, and 48% increase in tool life for cryogenically treated T1, M2, and D3 tools, respectively, in comparison to the conventionally heat-treated tools. They postulated martensitic transformation or precipitation of fine alloying carbides as the mechanism causing improvement in wear resistance. Molinari et al. [21] examined the effect of deep cryogenic treatment on quenched and tempered AISI M2 and H13 steels and reported higher wear resistance for these steels compared to their conventionally treated structures. The increase in wear resistance of AISI M2 steel was attributed to increased hardness whereas of AISI H13 steel the increased wear resistance was explained by its increased toughness due to cryogenic treatment. Huang et al. [23] suggested that cryogenic treatment not only assists carbide formation, increase in the carbide population and increase in its volume fraction but also makes the carbide distribution more homogeneous. Leskovsek et al. [24] reported that vacuum heat treated HSS, when subjected to cryogenic treatment results in increased wear resistance. These investigators mentioned that the observed beneficial effect can be related to suitable combination of the resulting fracture toughness and hardness of the steel. de Silva et al. [25] worked to verify the effect of cryogenic treatment on M2 HSS tools after using either laboratories or shop floor tests in an automotive industry. They reported favourable influences on the performance of the tools as supported by sliding abrasion, hardness tests and microstructural analysis. In a more recent work Yun et al. [26] investigated the influence of deep cryogenic treatment on the microstructures, mechanical properties, and service life of HSS tools and concluded that deep cryogenic treatment transforms retained austenite to martensite; while martensite gets decomposed, ultrafine carbides precipitate out. The precipitation of ultrafine carbides has been assigned as the primary cause in increasing the red hardness, strength, and toughness of HSS resulting into 100 % increase in the service life of disk mill cutter tools [26]. According to Collins [27], the precipitation of fine carbides during the cryogenic treatment cycle causes an increase in the wear resistance and in the tool toughness, but only a small, if any, in the tool hardness.

The review of the literature reveals the potential of use of cryogenic treatment in improving the performance of M2 HSS tools in turning of steels. But the available results in the literature pertaining to wear behaviour of M2 HSS tools subjected to cryogenic treatment are not coherent and the underlying postulated mechanism for achieving improved tool life is not well crystallised. The current study is therefore aim to study the performance of cryogenically treated single-point M2 HSS tools in orthogonal turning conditions.

2. MATERIALS AND METHODS

The tool material selected for the present investigation was M2 HSS which is generally used where the economical turning speed is too low to think about carbide tools. The commercially available square shaped (12mm×12mm×50mm) M2 HSS bits were procured and grinded on tool and cutter grinder to obtain tool signature as per IS:3019-1973. Tool signature of the used M2 HSS tools is presented in Table 1 and illustration of various tool signature angles is shown in Fig.1.

Table 1: Tool signature of the used M2 HSS tools (IS: 3019-1973)

<table>
<thead>
<tr>
<th>Tool signature parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orthogonal rake angle (α)</td>
<td>14°</td>
</tr>
<tr>
<td>Cutting edge inclination angle (γi)</td>
<td>4°</td>
</tr>
<tr>
<td>Orthogonal clearance angle (αc)</td>
<td>8°</td>
</tr>
<tr>
<td>Side clearance angle (αs)</td>
<td>8°</td>
</tr>
<tr>
<td>Cutting edge angle (λ)</td>
<td>60°</td>
</tr>
<tr>
<td>Side cutting edge angle (ω)</td>
<td>30°</td>
</tr>
<tr>
<td>Nose radius</td>
<td>0.4 mm</td>
</tr>
</tbody>
</table>

Fig.1 – Illustration of various tool signature angles.
nitrogen to eliminate the risk and damage of thermal shock. In order to avoid thermal shocks from rapid cooling and heating, the tools were cooled down and heated up slowly, to and from the shallow cryogenic temperature (−110 °C) and deep cryogenic temperature (−196 °C), over an 4h and 7h period respectively with the temperature being monitored by a thermocouple attached to the tools. This gives an average heating/cooling rate of 0.5 °C/min. After this, two tempering cycles consisting of heating to 150 °C were followed. Fig. 2 shows the heat cryogenic treatment cycle of SCT and DCT tools.

Fig.2 – Cryogenic treatment cycle for (a) SCT tools and (b) DCT tools.

Hot rolled annealed steel stock (C-45) of initial diameter 200 mm and length 800 mm was orthogonally turned on CNC turning machine (MSC-ZL25MC, Mori Seiki, Japan) by the M2 HSS tools belonging to all three groups (TT, SCT and DCT). Average values of maximum flank wear were recorded at each cutting speed after each predefined machining interval to minimize any possible error. Also for each cutting speed and tool group, 3 tools were used to get the average values of tool flank wear. It is important to be mentioned that a new tool was used for each turning machining test. The method of measuring tool flank wear in this study was in accordance to ISO 3685-1993. Studies so far have shown that the cutting speed is the most dominate factor influencing tool life, followed by feed and depth of cut, in that order [28, 29]. Hence, only the cutting speed was varied in three steps as 35, 45 and 55 m/min based on preliminary turning tests. All the cutting tests were performed at feed rate, f, of 0.1mm/rev and depth of cut, ap, of 1mm. Since the width of flank wear was not regular along the cutting edge, the maximum flank wear, VB_max, was measured using an inverted metallurgical microscope (DM ILM, Leica, Germany) after each predefined machining interval. The tools were inspected under the scanning electron microscope (F-200 FEI, Quanta, Holland) to excavate the possible wear mechanism. Oil-based coolant was pumped at rate of 3 l/min on the tool–work interface so as to flood the cutting zone along with surrounding area in all turning tests.

3. RESULTS AND DISCUSSIONS

The maximum flank wear (VB_max) values of the M2 HSS tools were measured at fixed machining intervals, i.e. after 3 min for cutting speed of 35 and 45 m/min whereas after 2 min for cutting speed of 55 m/min. Three graphs have been plotted for maximum flank wear (VB_max); one each for three cutting speeds and every graph has one curve each for TT, SCT and DCT tools as shown in Figs. 3–5. The representative optical images of used tools are shown in Fig. 6. The tool life of tools for all the selected cutting speeds are given in Table 2 and percentage change in tool life resulted from the application of cryogenic treatment (SCT and DCT) is given in Table 3.

![Fig.3 – Growth of maximum flank wear with machining time at cutting speed of 35m/min.](image)

![Fig.4 – Growth of maximum flank wear with machining time at cutting speed of 45m/min.](image)

![Fig.5 – Growth of maximum flank wear with machining time at cutting speed of 55m/min.](image)

![Fig.6 – Optical images of (a) TT, (b) SCT and (c) DCT tools used for cutting speed of 5 m/min.](image)
As reflected in the graphs (Figs. 3–5) for all the three cutting speeds, SCT and DCT M2 HSS tools resist wearing on flank face more effectively thus enhancing the working life of the cutting tools up to significant extent. From the graph shown in Fig. 3 for cutting speed 35 m/min, it is clear that the DCT M2 HSS tools performed comparatively better as compared with SCT and TT tools. Also, the DCT M2 HSS tools proved to be more effective in resisting wear as compared with SCT M2 HSS tools. The reported increase in tool life of DCT and SCT M2 HSS tools is 50.93% and 17.30% respectively as compared with TT M2 HSS tools. Also, DCT M2 HSS tools reported 40.67% increase in cutting life as compared with SCT. This considerable increase in tool life in DCT and SCT tools can be attributed to the morphological changes that might have occurred in the M2 HSS tool materials during cryogenic treatment. As the tool life gain obtained in DCT tools is maximum, it can be concluded that extremely low temperature treatments enables the M2 HSS tool material to resist wear more effectively. The changes occurred in metallurgy of M2 HSS material and the mechanism of tool flank wear will be discussed in the later part of the present paper.

From graph shown in Fig. 4, it is clear that the percentage increase in tool life of DCT tools (22.04%) as compared with SCT tools is not convincing enough for cutting speed of 45 m/min. This is contrary to the tool wear trend reported for relatively lower cutting speed of 35 m/min may be attributed to the high tool-chip interface temperature that might have destroyed the special properties induced in the cutting tools by cryogenic treatment. It is interesting to note that even at relatively higher cutting speed of 45 m/min, the minimum percentage increase in tool life reported (22.04%) is more than that of minimum increase in tool life reported in machining at cutting speed of 35 m/min (17.30%) though the overall service life of tools is comparatively short at cutting speed of 45 m/min. The service life of cutting tools kept on decreasing as we increased the cutting speed further to 55 m/min as shown in graphs presented in Fig. 5; however, the maximum percentage increase in tool life decreases as cutting speed was raised up to 55 m/min (47.99%). After critical analysis of data on percentage increase in tool life tabulated in Table 3, it can be concluded that more favourable results in term of long tool life can be expected by deep cryogenic treatment. It is apparent that the cryogenic treatment neutralized the adverse effect of possible higher tool-chip interface temperatures during machining thus helped in restricting flank wear of cutting tools.

Setting a maximum flank wear (VB\text{max}) of 0.6mm as tool life criterion, the tool life for each cutting speed was obtained. Plots of cutting speed and tool life on double logarithmic scale to base 10 for all the tools tested are shown in Fig. 7. It is apparent from the graph shown in Fig. 7 that the deep cryogenic treatment is more effective in increasing tool life at all cutting speeds. It can also be analyzed from the graph shown in Fig. 7 that the performance of cutting tools is more consistent for DCT tools as the dispersion of data points along the linear regression line for DCT tools (regression coefficient R^2 = 0.996) is less as compared with dispersion of data points along the linear regression line for SCT tools in (regression coefficient R^2 = 0.931) and TT tools (regression coefficient R^2 = 0.983). This may be one of the reasons for relatively superior surface finish of the machined surface on the work piece in case of DCT tools in comparison to SCT and TT tools. Moreover, this observation is also supported by the smaller cutting forces sensed manually on the cutting tools and lesser vibrations felt during turning while using DCT tools. However, quantitative and engineering analyses of these observations are beyond the scope of present study and can be taken for future research.

Table 2: Tool life (min) for maximum flank wear VB\text{max} = 0.6mm.

<table>
<thead>
<tr>
<th>Type of Tool</th>
<th>Cutting speed (m/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditionally heat treated</td>
<td>35</td>
</tr>
<tr>
<td>Shallow cryogenically treated</td>
<td>23.51</td>
</tr>
<tr>
<td>Deep cryogenically treated</td>
<td>28.43</td>
</tr>
</tbody>
</table>

Table 3: Percentage change in tool life for maximum flank wear VB\text{max} = 0.6mm.

<table>
<thead>
<tr>
<th>Cutting speed (m/min)</th>
<th>Angular tool life change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>45</td>
</tr>
<tr>
<td>Traditionally heat treated vs. Shallow cryogenically treated</td>
<td>17.50</td>
</tr>
<tr>
<td>Traditionally heat treated vs. Deep cryogenically treated</td>
<td>50.93</td>
</tr>
<tr>
<td>Shallow cryogenically treated vs. Deep cryogenically treated</td>
<td>40.67</td>
</tr>
</tbody>
</table>

Fig. 7 – Tool life of cutting tools vs. cutting speed on double logarithmic scale to base 10.

4. CONCLUSIONS

In the present work, the effect of cryogenic treatment on M2 HSS turning tools was evaluated in terms of tool flank wear. Summarizing the mean features of the results, the following conclusions may be drawn.

1. The shallow cryogenic and deep cryogenic treatment can significantly enhance the service life of M2 HSS turning tools, however the tools subjected to deep cryogenic treatment stand to gain relatively more as compared with shallow cryogenically treated tools. The recorded maximum tool life enhancement over traditionally heat treated tools in the present study is approximately 35% for shallow cryogenically treated tools and 50% for deep cryogenically treated tools.

2. Deep cryogenically treated turning tools of M2 HSS perform more consistently as compared to shallow cryogenically treated as well as traditionally heat treated tools. This might result in smaller cutting forces on the cutting tools and lesser vibrations during turning.

3. Through SEM images of tool flank wear, diffusion wear was identified as the dominated
wear mechanism in case of M2 HSS turning tools.
4. Cryogenic treatment causes morphological changes in the entire cross-section of the M2 HSS turning; hence, the same tool lives can be anticipated even after any number of resharpenings. Evidently, it is better to all type of coatings as the coatings become futile even after single resharpening of tool.

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