RELIABILITY OF ZTA CERAMIC CUTTING TOOLS WHILE MACHINING CARBON STEELS

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ABSTRACT:

Ceramic tools are finding increasing application the world over, especially to machine hard and HSTR alloys. Consequently, efforts to improve the quality besides reliability of such tools and find newer tools with higher hardness and toughness are being made by number of industries and laboratories. The present tools based on ZTA are developed and Performance tests on these tools were conducted using the facilities at the institute. It has been found that ZTA tools performed well at cutting speeds of 400 m/min and 600 m/min in addition have good reliability while machining 0.31% carbon steel (hardness of about 180 BHN).

Index terms: Zirconia Toughened Alumina (ZTA); High speed machining; Flank wear; Reliability; Weibull

1 INTRODUCTION:

Present day markets have stringent requirements for quality and precision in manufactured goods, which are frequently prepared with difficult-to-machine materials with exact specifications pertaining to dimensional accuracy, surface finish and product reliability.

Nomenclature

η= scale parameter, or characteristic life
β= shape parameter (or slope)
To meet these stringent requirements, difficult to machine materials (often having hardness of >45 HRC) necessitated strong cutting tools to machine them in hardened condition thereby reducing number of stages of manufacturing and frequent change of setups. Consequently, the design and construction of machine tools are vital in this new era of manufacturing engineering. Ceramic cutting tools are being used in advanced machine tools for their strength, stiffness, corrosion resistance, Surface finish and good thermal stability.

Ceramic products were first introduced in the 1980s. Silicon Nitride Spindles and bearings have better friction and wear characteristics than traditional metallic materials making them the perfect choice for maintenance-intensive applications as ceramic materials are having extremely low-friction and non-magnetic besides low specific weight. Due to this low density, these materials are suitable for the components of high speed machines which demand high system’s stability with low inertial forces [1].

Cutting ceramics can be divided into oxide (based on Al₂O₃), nitride (based on Si₃N₄) and SiC Fiber based composite ceramics. Nitride cutting ceramics are different from oxide cutting ceramics as the former have better persistence, but have lower chemical constancy for machining the steel [2].

2.1. RELIABILITY AS APPLIED TO CUTTING TOOLS
The reliability of cutting tools is a fairly new to technical field. This issue includes study, investigation and development of the cutting edge distinctiveness in the specified conditions and time period of operation that will operate within the specified parameters [3].
The concept of reliability is of paramount importance in cutting tools, since the productivity of computer integrated machining system is predominantly depends on accurate tool life estimation. At present, extreme unpredictability of the tool life is experienced due to which all the tools have to be removed from service, before the ‘shortest life of tool’ is estimated to fail. However, the cutting tools in any machining operations are expected to give a specified performance under specified conditions and with minimum machining cost over a given period of time. Generally this is determined by the reliability analysis of the cutting tools.

To evaluate the reliability of the cutting tools, it is necessary to conduct performance tests which may be of two types : (i) time censored and (ii) failure censored. Failure censored tests are convenient to record and are thus adopted in our present work. The flank wear of the tool has been selected as the standard criterion to decide the failure of the tool because flank wear is predominant in cutting tools rather than other failures.

The idea of determining the performance of the cutting tools was long ago acknowledged by Weibull when he put forth Weibull statistics to estimate the reliability of any engineering systems.

The aim of the paper is to investigate, recognize and analysis the factors which bring to the failure of the tools during the cutting process and their reliability. The cutting process is characterized by work material, tool material and the conditions of the working namely cutting speed, depth of cut, feed, and geometry of tool, coolants and the dynamic state of system: machine—Tool—work piece [4].

The current researches indicate that the probability functions of the cutting instruments failure will relied on the Weibull disperse [8,9].

\[ F(t) = 1 - \exp\left(-\frac{t}{\eta_0}\right)^\beta \]  

(1)

The reliability is the compliment of the probability;

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Frequency of failures is defined as follows:
\[ f(t) = \frac{dR(t)}{dt} \] (3)

The intensity of failures:
\[ \lambda(t) = \frac{f(t)}{dt} \] (4)

Investigations have been realized in theoretical and experimental ways, to get approximately data about failure event of the cutting tool while machining process from the aspect of utilization, crack and fracture. The problem that has been considered in this paper was the determination of reliability of the metal cutting tool at small and medium series by applying the medium rank method.

2.2. REPRESENTATION OF FAILURE PATTERNS BY WEIBULL DISTRIBUTION

Weibull distributions can be used to represent most of the failure patterns. The analysis is relatively simple and when followed through, enables us to decide a great deal about the failure mechanism. Correspondingly we can infer the following from the values of the Weibull parameters.

a) \( t_0 = 0 \). The item has no life of intrinsic reliability, and,
   i) if \( \beta < 1 \) the failure rate falls with age without reaching zero, so we should suspect early life characteristic arising from a low safety margin, giving raise to stress rupture failure.
   ii) if \( \beta = 1 \) the failure rate is constant for all ages which represent a random or pseudo-random failure characteristic or,
   iii) if \( \beta > 1 \) the failure rate increases with age at all ages which is indicative of wear out commencing as soon as the item was brought into service.
b) $t_0 > 0$. The item is intrinsically reliable from the time it was brought onto service until $t = t_0$, followed by

i) if $\beta < 1$ a fatigue or similar type of wear out in which the failure rate decreases with age after a sudden increase at $t_0$; low values of $\beta$ ($\sim 0.5$) may be associated with low cycle fatigue and higher values ($\sim 0.8$) with high cycle fatigue or,

ii) if $\beta > 1$ an erosion or similar wear out in which a constant load life continuously decreases with increasing load; lower values of $\beta$ suggest a constant load life which is more dependent on load than would be the case at higher values.

c) $t_0 < 0$. This could indicate the item was used or suffered failures before the date is collected, otherwise

i) if $\beta < 1$ it could be an early life failure mode beginning before the item was brought into service, arising from a low safety margin or,

ii) if $\beta > 1$ wear out by steady decrease of strength beginning before the item was brought into service.

Thus, it will be seen from the above that Weibull analysis can give a good lead to the mechanism of failure. It can often give a good insight into the mechanism involved [9,10].

3.1. DESCRIPTION OF EXPERIMENT

Reliability estimations are often based on either variable data or attribute data. The tests in which the actual life times are recorded is called variable life test and on the other hand if the data is recorded regarding the number if failures in a specified time, the tests are called attribute tests. On attribute basis the reliability is expressed as the ratio of the number items surviving the test to the total number of items put to test at a specified time.
The disadvantages associated with attribute testing are (i) the estimates are not superior and (ii) they are time dependent. On the other hand in the variable test, a probability distribution is assigned to the failure time which facilitates for the analysis and superior estimates of reliability are possible. Thus we select to perform the variable and data tests.

Again, the data needed for reliability analysis can be collected by any of the two types of testing namely (i) time censored test and (ii) failure censored test. In time censoring, the number of failures out of the total tested are recorded at a specified time where the testing is terminated, while in the case of failure censored tests, the test is terminated at the end of pre-assigned number of failures[8,9].

In both the cases the time to failure for each item may or may not be recorded depending on the type of test data desired, i.e., variable or attribute. Reliability test conducted can be either replacement or non-replacement type. In the case of replacement type the items failed during testing are replaced by new one. In contrast, in the non-replacement the failed items are not replaced.

3.1.1. STEPS INVOLVED IN RELIABILITY TESTS

The work material is carbon steel containing carbon content of 0.31%. The diameter of the work piece was 116 mm and the length of the same 400 mm, at the start of the experiments. The work material was pre-tuned to remove the rough surface. As far as possible, continuous turning was done without interruption. The steel bars were chamfered at an edge of 45° to the axis of the lathe, so as to avoid sudden loading of the tool at entry.

In these experiments variable data tests of the failure censored type( with replacement) were performed by turning carbon steel (0.31% carbon) using two sets of five ZTA tools each under two different working conditions. The cutting conditions are listed below. After each pass the flank wear was measured using tool maker’s
microscope as taken earlier. Tests on each tool were carried out till the flank wear reaches or exceeds 0.6mm.

3.2.1. TOOL MATERIAL

Zirconia Toughened Alumina (85 vol % Alumina + 15 vol% Zirconia), tools were used. The properties of the tools are given in Table 1.

<table>
<thead>
<tr>
<th>Tool material</th>
<th>Density g/cc</th>
<th>Porosity %</th>
<th>Hardness HV 20</th>
<th>Toughness MPa m½,</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZTA</td>
<td>4.358</td>
<td>0.02</td>
<td>1585</td>
<td>5.8</td>
</tr>
</tbody>
</table>

3.2.2. CUTTING TESTS

The facilities used in the experiments are: Lathe - VDF high speed high power Lathe (22 kW) continuously variable speed drive between 280 - 3550 rpm. Tool maker’s microscope for Flank wears measurement - Hilger – Watts; Surface roughness measurement – Mitutoyo surf test. The cutting conditions are given in Table - 2.

<table>
<thead>
<tr>
<th>Test</th>
<th>Cutting Speed, m/min</th>
<th>Feed, mm/rev</th>
<th>Depth of Cut, mm</th>
<th>Work material hardness, BHN</th>
<th>Nose radius, mm</th>
<th>Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test-1</td>
<td>400</td>
<td>0.1</td>
<td>1</td>
<td>180</td>
<td>1.2</td>
<td>ZTA</td>
</tr>
<tr>
<td>Test-2</td>
<td>600</td>
<td>0.1</td>
<td>1</td>
<td>180</td>
<td>1.2</td>
<td>ZTA</td>
</tr>
</tbody>
</table>
4. Results and Discussion

4.1. Flank wear at Different Speeds

Flank wear Vs Machining curves are drawn for cutting speeds of 400 and 600 m/min and are shown in figure 1. The curves show that the distinguishing the regions of (i) Initial rapid wear (ii) gradual wear (iii) Failure region is delicate and differ from sample to sample.

Tool wear is a time dependent process. As cutting proceeds, the amount of tool wear increases gradually. The slope of the wear curve depends on cutting speed V, feed f, and depth of cut d. Among various parameters, cutting speed plays a vital role. As cutting speed is increased, wear rate increases, so the same wear criterion is reached in less time, i.e., tool life decreases with cutting speed. The same is visualized through the curves as discussed.
0.31% carbon steel, 180 BHN, Feed 0.1 mm/rev, Tool ZTA, Speed 400 m/min

Sample 1
Sample 3
Sample 5

Machining Time, Min
Flank Wear, mm

0.31% carbon steel, 180 BHN, Feed 0.1 mm/rev, Tool ZTA, Speed 600 m/min

Sample 1
Sample 2
Sample 3
Sample 4
Sample 5

Machining Time, Min
Flank Wear, mm

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Fig. 1. (a): Flank wear Vs Machining Time (min) at 400 m/min ; (b) Flank Wear Vs machining Time(min) at 600 m/min.

Surface roughness values, Ra, were taken into consideration and were measured after each pass and ensured that it has not crossed 2.4µm.

Figure 2 shows the metal removed per edge of cutting tool in cm$^3$, considering reliability of tools.

4.2. METAL REMOVAL RATES

Fig. 2. (a) Metal removed Vs Machining Time at different cutting speeds ;(b) Reliability Vs Machining Time at different cutting speeds.
After 15 minutes machining, metal removed was 600 and 720 cm³ respectively at 400 and 600 m/min of cutting speed. It is to be noted here that,

- Till, 15 minutes of machining, tools machining at 600 m/min have reliability of 80% and tools machining at 400 m/min have 100% reliability.
- However, after 18 min, cutting tools machining at 600 m/min have started failing and beyond, the tools failed completely.
- Average tool life of the tools machining at 400 m/min is higher, they have removed more metal in their life time.

The same can be clearly visualised in Figure 2(b), representing reliability % Vs Machining Time at various intervals and non-existence of the tools machining at 600 m/min after 18 minutes.

Trends of Metal Removal at different cutting speeds are shown in Figure 3 which illustrate, the metal removal is higher at 600 m/min cutting speed as compared to 400 m/min. This is quite obvious. However, the higher rate of failure at 600 m/min, beyond 16 min, makes them ineffective. The graph obviously demonstrates, the higher metal removal rates are possible at cutting speed of 400 m/min due to their survival for longer period.

![Trends of Metal Removal Rates at different intervals.](image-url)
4.3. FAILURE RATE

Failure rates of the samples shown in Figure 4 at the tested cutting speeds of 400m/min and 600 m/min, demonstrates that the samples showed constant ‘Failure rate mode’. The Failure rate is observed to be low in these tools as the failure curve has maintained fairly long and flat behaviour.

Fig. 4. (a) Failure rate Vs Time for Cutting Tools Machining at 400m/min;(b) Failure rate Vs Time for Cutting Tools Machining at 600m/min.

Failure-Suspension (MTTF) line of the given samples as shown in Figure 5 also strengthens the Failure rate pattern of these tested tools have not failed in wear-in-mode (infant mortality).
Fig. 5. (a) Failure/Suspension Curve Vs Machining Time (sec) at 400m/min; (b) Failure/Suspension Curve Vs Machining Time (sec) at 600m/min.

The nature of these tools are unlike general engineered products wherein, the failure rate function $\lambda(t)$ has a time-profile like a bath-tub cross-section which is categorized in three distinctive time zones, each corresponds a unique failure mode. The infant mortality or wear-in mode is normally short, with a high but declining rate. This can be due to defective parts, defective materials, damages in handling, out of tolerances etc. The Present samples tested have been developed over a period of time by modifying various parameters to have better tool life and reliability [8, 9].

The youth or constant rate is generally caused by random events from without, rather than by inherent factors from within. In the youth period, the rate is constant and the associated Probability function (PDF) is one of exponential function. Random failure can be reduced by improving product design, making it more robust with respect to the service conditions to which it is exposed in real life.

The aging or wear-out mode is usually due to material fatigue. The wear-out mode is often encountered in mechanical systems and in this situation, cutting tools.
The random failure or constant rate mode, on the other hand, is widely used as the basis for product reliability considerations [8].

4.4. RELIABILITY OF CUTTING TOOLS

4.4.1. Reliability versus machining time curves were drawn for cutting speeds 400 and 600 m/min by using 2P Weibull at 90% confidence level. The curves shown in Figure 6, show uniqueness in shape. Reliability is in the order of 100% up to time period of 1800 sec, 0% at 3600 sec in case of cutting speed 400m/min. In case of cutting speed at 600 m/min, the values of reliability were 100% up to the time period of 700 sec, 0% at 1600 sec.

Fig. 6. (a) Reliability versus machining time(sec) at 400 m/min; (b) Reliability versus machining time(sec) at 600 m/min.

4.4.2. CONTOUR PLOTS IN WEIBULL++ AND ALTA

Contour plots are used for comparing specifics data sets. Considering two data sets, one at a cutting speed of 400m/min and another at 600 m/min for similar set of cutting tools of ZTA, the engineer would like to determine if the two plans are significantly different and at what confidence.
Figure 7.(a) Contour Plot when machining ZTA tools at 400 m/min (β vs η); (b) Contour Plot when machining ZTA tools at 600 m/min (β vs η).

By closely observing the Contour Plots in Fig.7.(a) and (b), there is no overlap between the two contours, hence the two data sets are significantly different with a 90% confidence.

Further, values of β are varying from 5 to 20 for cutting speed of 400 m/min and 4 to 28 for cutting speed of 600 m/min.
Figure .7.(a) Probability density function of ZTA tools at 400m/min ; (b) Probability Density Function of ZTA tools at 600m/min.

Finally, the probability density function graphs as shown in 7.(a) and (b) will give a clear idea of the life of ZTA tools and the period at which maximum failures occur at cutting speeds 400m/min and 600m/min. These findings also concurs the nature of tools and reliability in High speed machining environment [6,7].

5. CONCLUSIONS

According to theoretical work and experiments carried and the analysis based on Figure 6, can be concluded that,

- The reliability of cutting tool during the actual work conditions can be higher by 10-15% compared to laboratory/in-vitro conditions.

This difference is believed to be for the following reasons:

- During the development stage in the laboratory, the coolants were not used.
- In the development phase, cutting edge was engaged for several hundreds of seconds continuously compared to the actual field operating conditions of tens of seconds. Consequently, in real life conditions, we will not encounter such high temperatures.
- Length of Cutting chips during in-vitro conditions were highly continuous and longer, influencing the durability of cutting edge.

REFERENCES


