Surface Quality and Tool Wear in Interrupted Hard Turning of 1137 Steel Shafts

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1. INTRODUCTION

The machining of hardened steel components with PcBN inserts having a geometrically defined cutting edge has gained substantially in importance due to improvements in the performance of such modern cutting tool materials. Hard turning is increasingly a profitable alternative to finish grinding. The objective is to remove workpiece material in a single cut rather than a lengthy grinding operation, thus reducing processing time and production costs.

Many studies have been carried out in the hard turning of continuous surfaces and the success of this method has encouraged in the recent years studies in the interrupted hard turning area [1], [2]. An interrupted cut occurs when the non-uniform shape of the workpiece disrupts the otherwise smooth removal of material. Consequently interrupted hard turning can be defined as a turning process of hardened parts (>45 HRC) having areas with interrupted surfaces.

The studies in the interrupted hard turning field have concentrated mostly on tool wear evolution or mechanism [1], [4]. For continuous hard turning the maximum tool wear land width (VB_{max}) shows a near linear increase with cutting distance after initial rapid wear [3]. The same effect has also been noticed for interrupted hard turning [1]. On the other hand, tool life has been found to be very sensitive to both cutting speed and frequency of interruption [4]. More recent studies [5] highlight that the low-content CBN tool is superior to a high–content CBN tool in terms of tool wear and surface integrity for intermittent hard turning. The cutting force decreases with the increase of the cutting speed while the thrust cutting force increases significantly with the increase of tool wear.

In terms of surface finish the roughness parameters taken into consideration are generally the average roughness R_a and average maximum height of the profile R_z [6], [7], [8]. Results come mostly from studies of continuous hard turning. According to some authors [9] the main factors that have a direct influence on surface quality are the corner radius of the cutting edge and the feed rate. Generally speaking, the greater the feed, the greater the value of R_a; however, this is still influenced by the occurrence of tool nose chipping or surface cratering [4].

When analyzing surface quality in hard turning, special attention was paid to metallurgical alterations in the superficial layer. Most common for hard turning is the occurrence of a white layer. White layer is a result of microstructural alteration. It is called “white” layer because it resists standard etchants and appears white under an optical microscope (or featureless in a scanning electron microscope). In addition the white layer has high hardness, often higher than the bulk [10]. Authors [10], [11] claim that the white layer has a mixed martensite and austenite structure.

Typical materials that are hard-turned are 5120 steel (62 HRC), 1050 steel (62 HRC), 9310 (60 HRC) and 4320 steel (60-62 HRC) [12]. However, other steels are constantly used on a large scale in industry and their behavior in terms of hard turning is still insufficiently explored.

This paper presents the results of an experimental study of hard turning of a spline shaft made of 1137 steel hardened to 47 - 50 HRC. The goal was to obtain a similar or better surface finish as in case of grinding for the external interrupted surface (OD turning) defined by ten splines. Two types of cutting tools were first analyzed from the viewpoint of tool wear and surface roughness. The wear of the cutting inserts was evaluated and recorded using optical and SEM microscopy. After choosing the most suitable insert for interrupted cutting, a mathematical model for average roughness prediction was determined using Response Surface Methodology. The response variable was the average surface roughness, R_a, and it was investigated as a function of the cutting regime (feed, cutting speed, and depth of cut) for a given geometry of the cutting tool. The workpieces used for wear trials were also analyzed from the viewpoint of superficial layer transformations, pre-eminently occurrence of white layer.

2. EXPERIMENTAL SETUP

The component parts considered for this study are spline shafts made of 1137 steel, induction hardened to 47 - 50 HRC. Figure 1 presents the component part and the surface (IS) that was machined.

This type of steel is widely used for parts where a large amount of machining is necessary, or where threads, splines or other operations offer special tooling problems. Table 1 presents the chemical composition of 1137 steel.

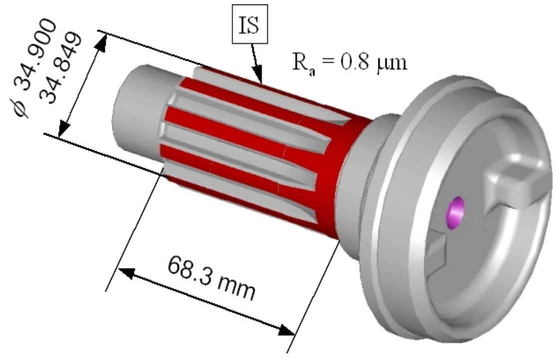

Figure 1. Spline shaft 1137 steel, 3D view

Table 1. Chemical composition of 1137 steel

%C	%Mn	%P (Max.)	%S (Max.)
0.32 - 0.39	1.35 – 1.65	0.040	0.08 – 0.13

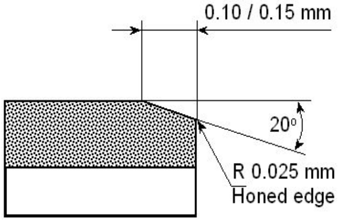

Figure 2. Edge preparation for PcBN inserts

The cutting tools considered for this research were specifically designed for hard turning applications and are relatively new on the profile market. One type of PcBN insert is AMBORITE DBC50 and the other type AMBORITE DBN45. Both types have the same nose radius, equal to 0.8 mm.

DBC50 is a low content, fine grain PcBN material on a tungsten carbide base. The CBN content is 50% by volume in a TiC binder phase, and the average CBN grain size is 2μm. DBN45 is a low content PcBN material (45% - CBN) with a sub-micron grain size integrally bonded with a titanium nitride (TiN) ceramic binder onto a tungsten carbide base. The cutting edge preparation is the same for DBC50 and DBN45 and consists of a chamfer at 20^0 from the rake face and a hone of the active edge. Figure 2 presents the edge preparation characteristics.

3. RESULTS AND DISCUSSIONS

3.1. Flank wear investigation

Maximum flank wear land width (VB_{max}) was monitored as a function of cutting length. The cutting regime considered was: depth of cut a = 0.18 mm, cutting speed V = 125 m/min, and feed f = 0.15 mm/rev. No coolant was used – dry turning. The number of passes between two measurements was chosen 8 for each type of component part. The wear analysis consisted in optical investigation (using a stereo microscope) of the inserts and measurement of the maximum flank wear land width, plus SEM observation of the worn area. Same number of passes has been done with each type of cutting insert. The wear experiments have been replicated (the same cutting parameters and mountings were used). An additional test has been performed for higher cutting speed, V = 175 m/min, the other parameters remaining unchanged (depth of cut a = 0.18 mm, feed f = 0.15 mm/rev). The preset tool life criterion was that when maximum flank wear land width becomes equal or greater than 0.2 mm, the tool life ends.

Figure 3 presents the VB_{max} versus cutting length for the first series of wear tests while figure 4 presents the results for the replicated wear tests. Figure 5 presents the wear evolution in case of high-speed tests, V = 175 m/min. It can be remarked for all tests that the flank wear in case of using DBC 50 is higher comparing to DBN45. However, in first two cases it is considered that the differences are not significant enough to specify with certitude which type of insert has a better behavior for interrupted hard turning. This situation is considered to be a result of the fact that the cutting process was interrupted to often in order to take measurements of the flank wear so a stable cutting regime could not be reached. The difference in the PcBN inserts behavior becomes more significant when the interval between two measurements of wear is increased to 16 and while the cutting regime is tougher – see last two measurements for the higher speed case (V = 175 m/min) on the chart from figure 5.

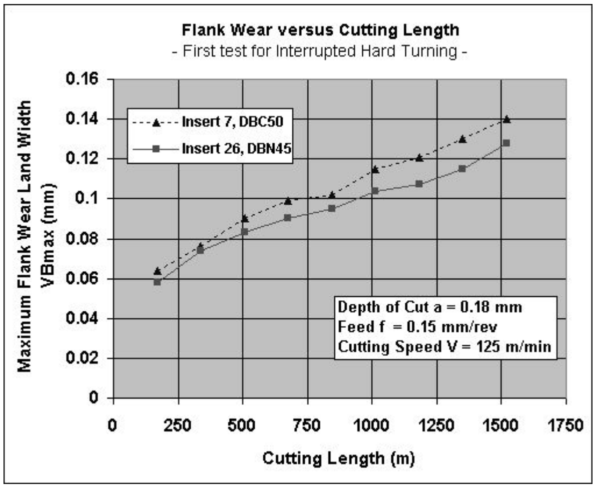

Figure 3. Initial wear tests

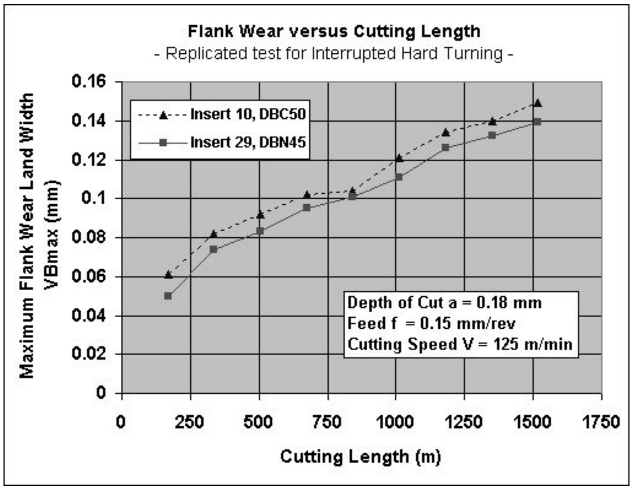

Figure 4. Replicated wear tests

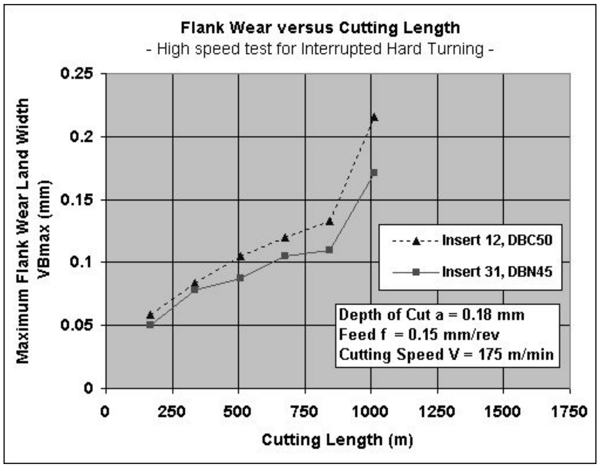

Figure 5. Initial wear tests

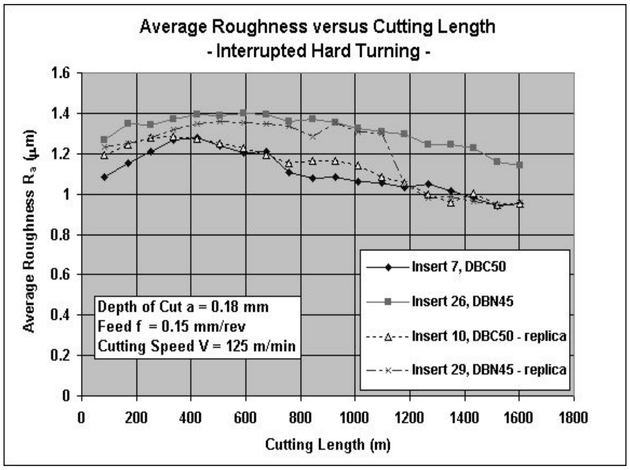

Figure 6. Replicated wear tests

Figure 6 presents the average roughness evolution for the component parts used for wear experiments. It can be remarked that for all the situations the roughness has an initial increase followed by a plateau stage and then by a slow decrease. This behavior of R_a is also encountered in common turning and it is explained by the fact that while the flank wear increases the cutting edge becomes 'dull' in the contact area. As a result, the depth of the tool traces on the workpiece surface tends to decrease and consequently the Ra decreases as the cutting edge accommodates the workpiece surface.

The SEM analysis performed in case of interrupted cutting revealed wear patterns similar to abrasion wear patterns. Grooves parallel to the movement of chip/workpiece material could be remarked. It is considered that these grooves are provoked by the hard particles from workpiece material and by the CBN grains pulled out through an attrition process and due to the removal of the ceramic binder through abrasion. Figure 8 presents the flank wear in case of DBN45 insert type; besides the fine vertical grooves that were remarked on the tool flank, traces of adhered layer could also be seen, mostly under the flank wear region. A much thicker adhered layer was also found on the rake face for both types of PcBN inserts. Figure 7 presents the chamfered edge of a DBC50 insert with such an adhered layer. EDS (Energy Dispersive Spectrometer) analyses confirmed that material from the workpiece adhered to the cutting insert. It is assumed that during cutting the adhered layer has a protective effect against abrasion mostly for the rake face and lesser for the flank of the insert.

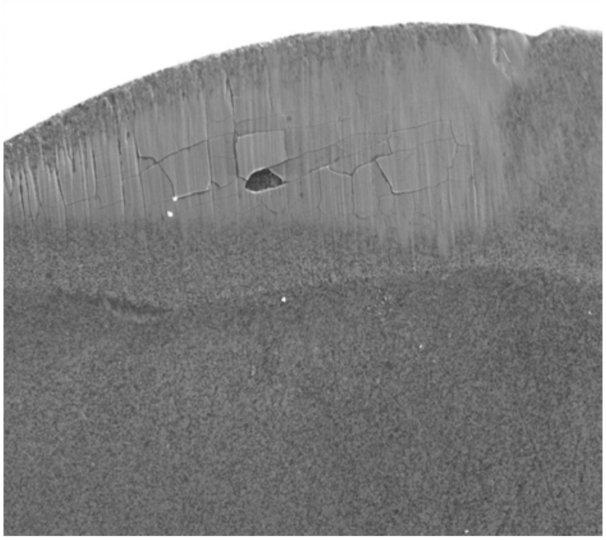

Figure 7. Adhered layer on hamfered cutting edge, Insert 7, DBC50, 250X

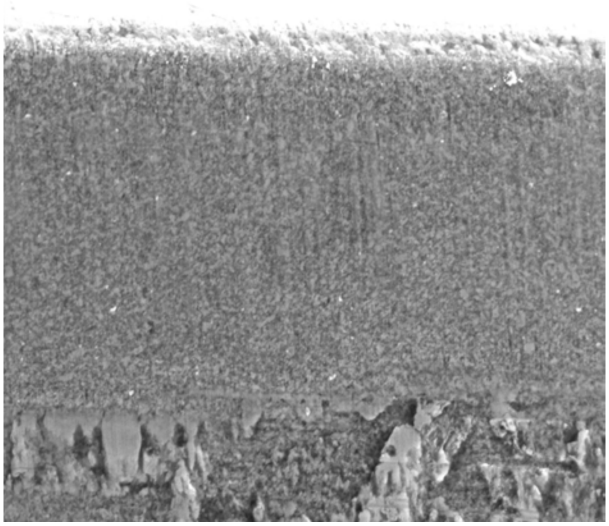

Figure 8. Flank wear pattern (DBN45, 250X)

3.2. Analysis of Surface Finish

The factorial technique was used to analyze the evolution of average surface roughness R_a versus the cutting regime. A preliminary experiment of mixed 3^2 factorial was first conducted varying only feed and cutting speed. Following the results obtained during the preliminary experiment, a replicated 3^3 factorial experiment was designed in order to determine an accurate predictive function for R_a versus the cutting regime. The intervals considered for the parameters of the cutting regime were chosen within the recommended operating values of the PcBN inserts: feed f = 0.025 to 0.229 mm/rev, cutting speed V = 100 to 150 m/min, and depth of cut a = 0.102 to 0.254 mm. The experimental matrix for the 3^3 design is presented in table 2. The factorial experiment was completely randomized. The dedicated software STATGRAPHICS *Plus* 5.0 was used as aid tool for statistical analysis of the recorded data.

Table 2 Experimental matrix for 3^3 design

Factors of influence / Levels	Feed (mm/rev)	Cutting Speed (m/min)	Depth of Cut (mm)
Low	0.025	100	0.102
Medium	0.127	125	0.178
High	0.229	150	0.254

According to [13] the terms containing third factor interactions can be neglected, as they do not have a physical interest. From this reason, only the second order factors were considered. The initial analysis of variance proved that feed is the most significant factor. Depth of cut was found to be also a significant factor but its influence is much lower comparing to the cutting feed. The effect of cutting speed can be neglected. However, in an initial approach the residuals versus predicted values chart suggested that a transformation of the response variable should be performed. Several transformation were tried for R_a and the solution considered best was found to be for the following conditions: maximum order effect considered for the analysis is 2, a normal logarithm transformation is applied to the response variable. The optimization of regression equation was made in terms of R-squared and the chart of residuals versus predicted values. Finally, the results of analysis of variance for this optimal case are presented in table 3.

Figure 9 presents the response surface for the transformed variable Log(Ra) while figure 17 presents the response surface for R_a versus feed and depth of cut. The predictive model was experimentally validated for cutting regimes different from those considered for the factorial design. Additionally, a study of optimum cutting parameters in terms of reaching and maintaining the prescribed surface roughness R_a = 0.8 μm was completed. It was obtained that the prescribed value of R_a can be easily achieved and maintained while maintaining the dimensional accuracy of the workpiece. Considering a minimum cutting time criterion while applying a correction for tool wear, the optimum cutting regime was found: f = 0.102 mm/rev, a= 0.178 mm, and v = 125 m/min.

Table 3. Analysis of Variance for Log(Ra)

Source	Sum of Squares	DOF	Mean Square	F - Ratio	P -Value
A:Feed	65.9761	1	65.9761	3712.97	0.0000
C: Depth of Cut	0.245545	1	0.245545	13.82	0.0005
AA	3.26228	1	3.26228	183.59	0.0000
Lack-of-fit	0.140475	5	0.028095	1.58	0.1838
Pure error	0.835147	47	0.0177691		
Total	83.3842	55			
R^2 = 98.6153 % $R^2_{adjusted}$ = 98.5355 %	The equation of the fitted model is LOG(R_a) = -2.44022 + 25.5698*Feed - 1.08668*Depth of Cut -48.4159*Feed^2				

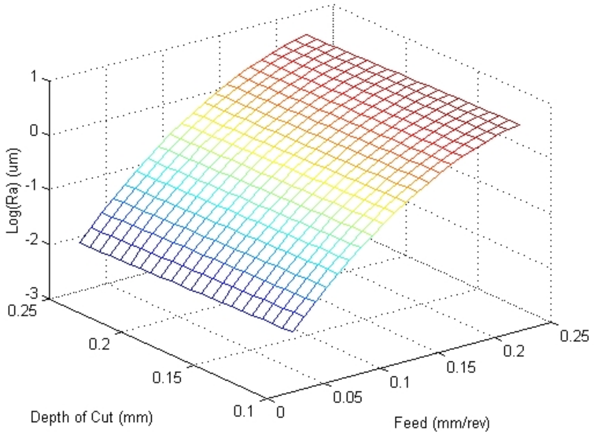

Figure 9. The response surface for Log(Ra)

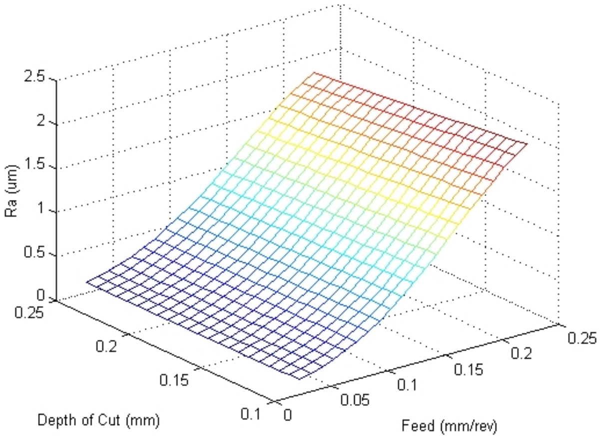

Figure 10. The response surface for Ra

A study of surface topography revealed a similar pattern of the machined surface as for common turning of steels, as long as the insert was not worn. Figure 11 shows such a pattern captured through a ZYGO instrument. While the cutting insert starts to wear off, the profile of surface changes from the classical helix shape (figure 11 – 1) towards a more and more irregular shape as in figure 11, 2) and 3). This change of profile with time is directly related to tool wear.

It can be remarked that while in terms of Ra hard turning can easily achieve surface finish comparable or better than grinding, in terms of other surface finish parameters, further investigations need to be performed.

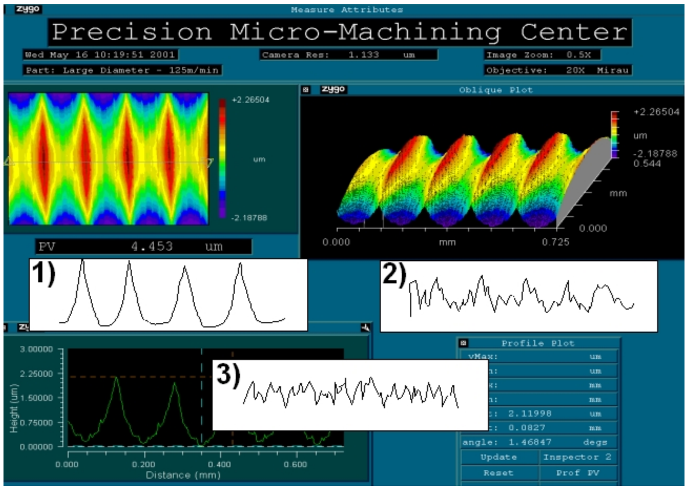
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Figure 11. Topography of hard turned surface

3.3. White Layer investigation

The white layer evolution was investigated only as a function of flank wear of the insert. Samples were cut from workpieces involved in wear experiments. The samples were further nickel covered to avoid edge rounding during polishing. Both longitudinal and transversal areas of the machined surface were investigated. It could be remarked that only for the highest values of VB_{max} (over 0.17 mm), the white layer starts to have a consistency, in all the other samples being no certitude for consistent white layer consideration. The maximum thickness of the white layer observed was found to be not bigger than 0.007 mm. A darker layer could be remarked under the observed white layer. It is inferred that the dark layer is overtempered martensite but more research has to be done in this area.

4. CONCLUSIONS

The hard turning of 1137 steel shafts has been successfully completed. The 1137 steel did not raise any specific problems to the PcBN inserts used for these experiments. AMBORITE DBN45 made proof of better performance in interrupted cutting.

The main wear mechanism for the PcBN inserts was found to be the abrasion of the binder material by the hard particles of the workpiece and the loose CBN grains pulled out during the cutting process. It is assumed that the CBN grains are pulled out due to a combined abrasive/attrition wear action. A protective layer made of workpiece material builds up mostly on the rake face. It is presumed that at higher speed the adhered layer becomes softer and it is easily scratched and penetrated by the hard particles thus accelerating the wear.

No consistent white layer was remarked but for high values of insert flank wear, closer to tool life limit.

A regression equation that predicts average roughness of the hard turned surface versus cutting regime was determined. Feed was found to be the most significant factor of influence followed by the depth of cut that, however, has a much lower influence. The lowest significance belongs to the cutting speed, which was not considered in the equation. An optimization of the cutting regime for the prescribed roughness was performed. The dimensional accuracy could be achieved and maintained throughout this study.

An investigation of surface topography showed a similar pattern of the machined surface as for common turning of steels as long as the insert was not worn. While the cutting insert starts to wear off, the profile of surface changes and becomes irregular. Further studies involving different roughness parameters becomes necessary in order to completely characterize the surface finish obtained through hard turning.

5. REFERENCES

[1] Chou, Y. K., Evans, C. J., "*Cubic boron nitride tool wear in interrupted hard cutting*", Wear 225 – 229, (1999), pp. 234-245.

[2] Dawson, Ty G., Kurfess, R. T., "*Hard turning, tool life, and surface quality*", Manufacturing Engineering, April 2000, pp. 88 – 98.

[3] Chou, Y. K., Evans, C. J., "*Tool wear mechanism in continuous cutting of hardened tool steels*", Wear 212 (1997), pp. 59-65.

[4] Lin, Z. C., Chen, D. Y., "*A study of cutting with a CBN tool*", Journal of Materials Processing Technology, 49 (1995), 149-164.

[5] Ko, J. T., Kim, S. H., "*Surface integrity and machineability in intermittent hard turning*", The international Journal of Advanced Manufacturing Technology, No. 18, 2001, pp. 168 – 175.

[6] Knuefermann, M. M. W., Read, R. F. J., Nunn, R., Clark, I. E., Fleming, M. A., "*22 nm R_a surface finish achieved with AMBORITE DBN 45 in ultra-precision turning of hardened steel*", Industrial Diamond Review, No. 2, 2001, pp. 87 – 92.

[7] Liu, C. R., Mittal, S., "*Single-Step Superfinishing Using Hard Machining Resulting in Superior Surface Integrity*", Journal of Manufacturing Systems, Vol. 14/No. 2, 2001, pp.129 – 133.

[8] Sood, R., Guo, C., Malkin, S., "*Turning of Hardened Steel, Society of Manufacturing Engineers*", MR99-241, 1999, pp.1-12.

[9] Klocke, F., Lung, D., Liermann, J., Rottger, K., "*Part quality in hard turning*", 1997,pp. 389 – 400.

[10] Griffiths, B. J., Furze, D. C., "*Tribological advantages of white layers produced by machining*", Transactions of ASME, 1987, 109, pp. 338 – 342.

[11] Chou, Y. K., Evans, C. J., "*White layers and thermal modeling of hard turned surfaces*", International Journal of Machine Tools & Manufacture 39, 1999, pp. 1863 – 1881.

[12] Hasan, R., "*Why are you still grinding?*", Manufacturing Engineering, February 1998, pp. 76-78.

[13] Montgomery, D. C., "*Design and Analysis of Experiments*", John Wiley & Sons, Inc., 2001.