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Metal Removing Thermal Stress Influences on Hardness and Tensile Strength Properties of Machined Items for Aeronautic Applications

Shehret Tilvaldyev[1], Arturo Paz Pérez[1], Manuel Alejandro Lira Martínez[1], Cardenas Dominguez Itzel Daniela[1]
[1]Instituto de Ingeniería y Tecnología, Universidad Autónoma de Ciudad Juárez. Ave. Del Charro 450 N Cd. Juárez Chih. CP 32310, México

Abstract— *The heat of metal removing process has critical influences on properties of machined item and can cause thermal damage and conflicts directly with the demand for increased production efficiency. The grinding process requires a very high input of energy per unit volume of material removed. A significant portion of the energy is converted to heat, which is concentrated within the grinding zone, thereby leading to high temperatures and possible thermal damage to the work-piece. The effect of grinding-induced heat on Hardness and Tensile strength of machined steel in metal removing process has been investigated using manufacturing equipment, temperature controlling methods, mechanical properties testing machines and microscope (ESM) for laboratory experiments. The relationship between the residual thermal stresses in the surface region, caused by grinding, and changes of some mechanical properties of the machined steel is elucidated.*

Keywords— *Hardness property, heat in grinding zone, tensile strength property.*

I. INTRODUCTION

Grinding is an important machining process that uses bonded abrasives to remove surface material, and can lead to residual stress in the near-surface layers of the remaining work-piece. In grinding, most of the consumed power is transformed into heat, thereby generating possible high temperatures in the contact zone between the wheel and work-piece [1–3]. The high temperatures at the wheel–workpiece interface may cause thermal damages to the work-piece material [4–7]. In order to analyze the effects of various grinding parameters on the temperatures generated at the contact zone, many previous studies have been conducted in an attempt to establishing a theoretical model to cover temperature characteristics in grinding with wheels of continuous structure. King and Hahn [8] were the earliest authors who have discussed the influence of wheel speed on grinding power and have determined experimentally that very low or very high wheel speed may require high grinding power. Their results show that optimum wheel speed in most cases is in the range of 8000-10,000 RPM; at higher or lower speeds, thermal damage is more likely to occur. Nowadays, thermal analyses of grinding processes are usually based on Carslaw and Jaeger's early work of a sliding heat source model [9-10]. In Carslaw and Jaeger's model, a heat source moves with a constant velocity along the surface of a semi-infinite solid, under an assumed quasi-steady state heat transfer condition. Hae-Ji Kim et al. [11] presented that the scalene triangle model was particularly suitable for estimating the work-piece temperature. In fact, both theoretical and experimental studies [12-14] have shown that the heat generated in grinding can be approximated reasonably by a scalene triangular heat flux which moves along the positive direction of x-axis on the work-piece surface.

Malkin et al. [15] provided a comprehensive overview of thermal analyses for grinding processes and the effect of grinding temperatures on thermal damage to the work-piece. Thermal models have been developed which take the most important factors into account: depths of cut, work-piece velocities, and energy partition to the work-piece that can vary significantly depending of the type of grinding, abrasive grain material, and grinding fluid. An example of energy partition of 65% obtained by matching the maximum temperature distributions at various depths to the analytically computed temperature is shown by Gao et al. [14] for grinding of AISI 1020 steel work-piece with aluminum oxide wheel, triangular heat source and time constant = 4.3 msec. Some differences between Theoretical and Experimental measured values may be attributed to the Second Low of Thermodynamics: the thermal model assumes that all the 100 % energy expended by grinding is converted to heat, however it has been shown that about 3 – 10 % of the energy expended by plastic deformation may not be converted to heat [16].

Excessive grinding temperatures cause thermal damage to the work-piece, for example, the heat of grinding a hardened steel without any burning, generally induced some softening due to tempering close to the surface [17-19]. Starting with an initial hardness of about 8 GPa, a greater degree of tempering can be seen with increasing wheel depth of cut due to higher temperatures to a greater depth below the surface. Re-hardening of the steel work-piece also occurs towards the surface at the biggest depth of cut.

Temperature measuring methods do not provide a practical means to identify and control grinding temperatures in a production environment, as their use is generally restricted to the laboratory. Much more feasible approach to estimate grinding temperatures can be provided when real-time monitoring of the grinding power coupled with a thermal analysis of the grinding process.

Nowadays, grinding temperatures can be predicted quite well, but how the grinding temperatures affect the work-piece surface is not well understood.

II. Material, Methods and Experimental Procedures

In this work, the experimental procedures were used to obtain information (results) and investigate how the heat of surface grinding processes with *standard (normal) parameters* changes Hardness and Tensile strength properties of the work-pieces, and how the *increased (overloaded) grinding parameters* (Cutting velocity, Depth of cut, and the Material Removal Rate) changes heat influence and properties of material

2.1 Material.

One type of work-piece material for all grinding processes (the same initial physical and mechanical properties) was used – B1112 Steel, with 160 BHN hardness parameter, and 100 % Machinability Rating. For the experiments was prepared one 150 mm x 40 mm x 25mm *reference item*, and 21 the same dimension pieces of steel to grind on different machining parameters.

2.2 Machining Equipment.

Material removing process completed on Grinding (Hurco TM8) Machine with following variables: Depth of cut (d), [*mm*], Work-piece speed (V_w), [*m/min*], Wheel Speed (V_s), [*m/sec*], and Specific Material Removal Rate (Q_w), [$mm^3/mm.sec$]. Machining processes were completed by Grinding wheel with Aluminum Oxide (Al_2O_3) abrasive material, Table I.

TABLE I. Properties of grinding wheel's abrasive material.

Parameter	Aluminum Oxide (Al_2O_3)
Crystal Structure	Hexagonal
Density, [g/cm^3]	3.98
Melting point, [^oC]	2040
Knoop Hardness, [kg/mm^2]	2100

2.3 Temperature Measurement.

There are no simple reliable methods of measuring the temperature field. In this experiment temperature measured in the real machining process *directly* by means of temperature paints techniques, and *indirectly* by measuring the infrared radiation (FLIR 5). Remote measuring/inverse methods (FLIR 5) does not provide easy to read temperatures at the point of interest, where the cutter is in contact with the work-piece, but produces a temperature map, showing areas of similar temperature. Objects are shown in different colors to illustrate the different temperature zones.

2.4 Material Properties Testing Equipment.

Brinell hardness Test machine was used in attempt to examine the relation of the deformation of metal specimen to the hardness property of a metal. The specimen was mounted unto the machine and the machine was loaded with equivalent loads as indicated by the experimental procedure. The results were measured by help of a microscope, recoded, and tabulated. The Hardness testing processes completed in the current Standard: ASTM E 10, Standard Test Method for Brinell Hardness of Metallic Materials. WAW Computer-control electro-hydraulic servo universal testing machine (with maximum test force 1000 KN) was used to perform Tensile Strength tests of the initial (reference) and machined at very high (overloaded) parameters specimens.

2.5 Experimental Procedures.

First, we prepared material – one piece of B112 Steel as a reference (initial) specimen, and 28 same dimension pieces for the machining at different (from min to max) parameters of grinding processes. Fig. 1 showing the geometry of Surface Grinding and the cutting condition variables.

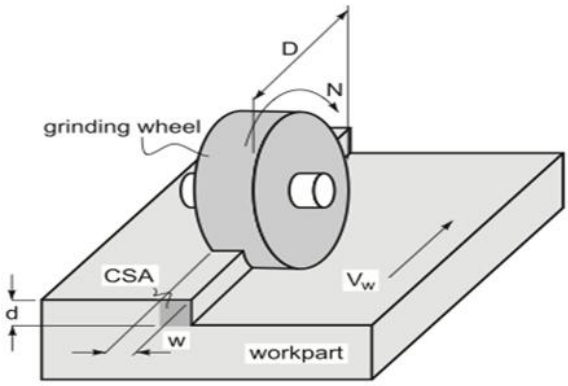

Fig. 1. Surface grinding geometry and cutting conditions.

The cutting velocity (V_s) in grinding is very high. It is related to the rotational speed of the wheel by

$$V_s = \pi DN$$

Where (D) is the wheel diameter and (N) is the rotational speed of the grinding wheel. Depth of cut (d) is called in feed and is defined as the distance between the machined and work surface. As the operation proceeds, the grinding wheel is fed laterally across the work surface on each pass by the workpiece. The distance at which the wheel is fed is cross feed, and is actually the width of cut (W). The cross feed multiplied by in feed determines the cross-sectional area of cut, CSA: CSA = crossfeed×infeed = W × d. The cross-sectional area in grinding is relatively small compared to other traditional machining operations. The work-piece moves past the wheel at a certain linear velocity called a feed (V_w). The material removal rate, (Q_w), is defined by $Q_w = V_w CSA$. Table II showing experimental processes matrix and Grinding variables.

TABLE II. Grinding process variables.

Machine Settings	**Grinding Approach I**	**Grinding Approach II**	**Grinding Approach III**
Depth of cut (d), [*mm*]	0.05 - 0.1	0.1 – 1.5	1.5 – 3.0
Work-piece speed (V_w), [*m/min*]	1 - 30	1 - 30	1 - 30
Wheel Speed (V_s), [m/sec]	20 - 60	20 - 60	20 - 60
Specific Material Removal Rate (Q_w), [mm^3/mm.sec]	0.1 - 10	10 - 45	10 - 60

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Next, the temperature controlled equipment and materials were prepared to measure (directly and indirectly) the heat distribution during the cutting processes. Than metal removing (grinding) process were performed and taken temperature measurements. Finished work-piece cooled down at room temperature. We repeated this process for the other specimens, each time increasing machining parameters according the experiment matrix (Table II). For each machining process used well dressed grinding wheel. Finally, we used SEM (scanning electron microscopy) to investigate any structural changes and Brinell hardness Test machine to test the reference specimen and machined items to examine the properties of a metal, and analyzed collected data.

III. Results and Discussion

Even though we are studying how the heat changes mechanical properties of the finished wok-piece, and not investigating the heat dynamics in grinding zone process, is necessary to discuss the most important approximations of the heat interference in tool-cheep-workpiece area. The heat problem is not so serious in traditional grinding helped with cooling fluids, but may be important when increasing productivity, in high precision work, and when the use of cooling fluids is not appropriate. In grinding, nearly all of dissipated energy is converted into heat that in turn raises the temperature in the machining zone. According to the Thermodynamics 2-nd Low the heat flows spontaneously from a hot area to a cool one, and heat in grinding zone dissipated in: a) cheep-tool-workpece unit, and depends of thermal conductivity of the items; b) solids (cutting zone) and environment. The heat generated is shared by the chip, cutting tool and the blank. The apportionment of sharing that heat depends upon the configuration, size and thermal conductivity of the tool-work material and the grinding condition. After several minutes up to one hour, depending on size of finished work-piece, heat ultimately will flow to the environment. The amount of energy stored elastically in the solids is negligible. The maximum temperature at grinding surface *significantly increases* with increasing of Grinding Depth (d), *mm* Fig. 2, and speed (V_w) of Work-piece, Fig. 3.

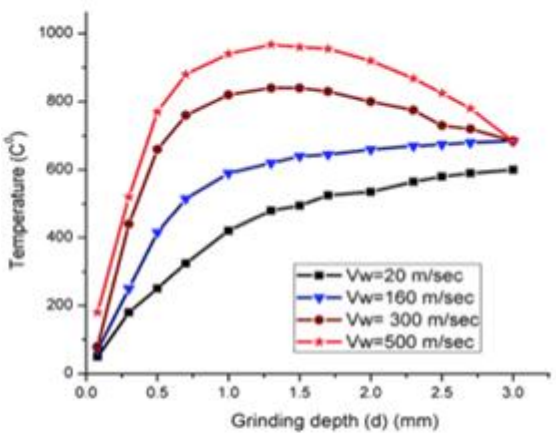

Fig. 2. Maximum tenperature (°C) versus grinding depth (d), [mm], at four different Work-piece speed (V_w), [*m/min*].

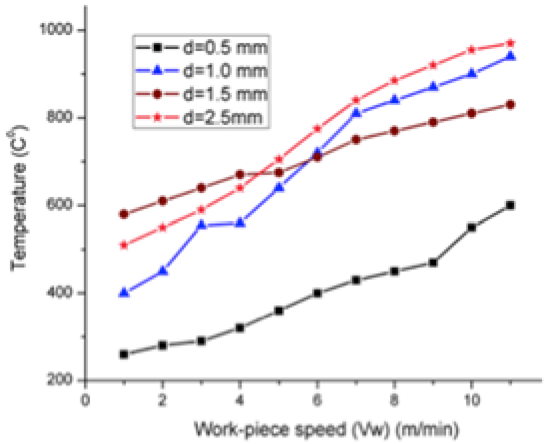

Fig. 3. Maximum tenperature (°C) versus work-piece speed (V_w), [*m.min*], for different cutting depths (d), [*mm*].

It is observed (Fig. 2), that the heat in grinding zone significantly rises from room temperature to 800° C, when grinding depth (d) increases up to 0.5 mm for work-piece machined at speed (V_w) 500 mm/sec; to 670° C at work-piece speed 300 mm/sec, than intense of temperature's dynamics lowers to 800° - 950° C, when grinding depth (d) rises to 1.2 mm, and further does not increases, even though the grinding depth extents to 3.0 mm. The temperature does not rises at high grinding depth (d) and work-piece speed (V_w), because great amount of heat dissipated with very fast forming and removing chips, preventing diffusion of the heat in work-piece and grinding wheel. Heat generation and surface temperatures in grinding zone are highly depended on grinding depth (d), because cutting interface area increases when grinding depth extends. Results of the experiments (Fig. 3) show, that the temperature at grinding surface does not significantly depends on work-piece speed (V_w): when speed increases 10 times, the temperature in machining zone rises maximum 2.15 times for all variation of depth (d).

Hardness is the property of a material (metal) by virtue of its ability to resist abrasion, indentation (or penetration) and scratching by harder bodies. It is the resistance of a material to permanent deformation of the surface. In other words, one can define it as the resistance of the metal to penetration by an indenter. The hardness of a surface of the material is, of course, a direct result of inter-atomic forces acting on the surface of the Material. We must note that hardness is not a fundamental property of a material, however, but rather a combined effect of compressive, elastic and plastic properties relative to the mode of penetration, shape of penetrator, etc. Hardness seems to bear a fairly constant relationship to the tensile strength of a given material and thus it can be used as a practical non-destructive test for an approximate idea of the value of that property and the state of the metal near the surface. All hardness tests are made by penetration a hardened steel ball into the testing surface, and Brinell Hardness Test machine was used in attempt to examine the relation of the deformation to the hardness property of a metal. The specimen was mounted unto the machine and the machine was loaded with equivalent loads as indicated by the experimental

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procedure. The results were used to plot graphical curves and presented in Fig. 4.

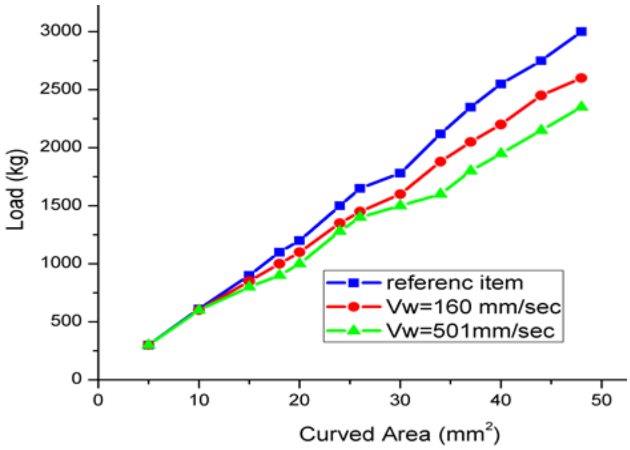

Fig. 4. Hardiness diagrams for reference and grinded B112 steel at work-piece speed V_w =160 mm/sec, and 500 mm/sec.

Series tests was made for all 22 items, but diagrams in Fig. 4 shows results only for three of them: reference (initial) specimen; work-piece, that was machined on the highest parameters, inducing the maximum temperature in machining zone (Grinding Depth – 1.35mm and work-piece speed – 500 mm/sec); and work-piece grinded at 160 mm/sec speed and 3mm depth. The data for the rest 19 tested items positioned in between presented on the graph two polar (minimum and maximum) lines. The graph shows, that Curved Area on the tested surfaces of the reference and machined items does not have noticeable difference under the application of Load up to 1000 kg, and this difference less than 2 mm^2. Significant difference (8 mm^2) in deforming surface areas appears, when applied Load equal 2600 kg. Maximum Curved Area (48 mm^2) forms under the Load of 2300 and 2600 kg for the machined work-pieces, and 3000 kg – for the reference (initial) steel. So, we can state, that hardness property of the testing steel degrades if the heat induced by grinding process increases temperature in cutting zone more than 850^0 C.

Hardness is the state of the metal near the surface, and we consider it as a surface property. We performed in laboratory Tensile Strength tests to analyze how the thermal stress in work-piece, induced by heat in grinding zone, affect on volume property of the steel. For the test were prepared two specimens: one - from reference item and another – from grinded at higher machining parameters work-piece. Diagram in Fig. 5 shows Tensile Strength test results for the two items: reference (initial) steel and finished work-pieces, heated during the machined process up to 850^0 – 980^0 C, and cooled down in room environment. Stress, under the application of pressure up to 440 MPa, does not induced any deformation in testing items. Strain appears, and makes significant deformation of testing elements, when stress rises close to 600 MPa, but dynamics and character of the Strain deformations for both of testing specimens the same and almost identical.

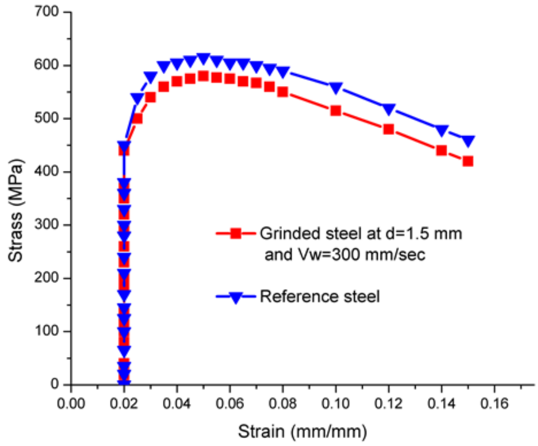

Fig. 5. Stress – Strain diagram for reference and machined B112 steel (Grinding Deep d = 1.5 mm, and work-piece speed V_w = 300 mm/sec).

The thermal stress from high temperature in grinding zone (up to 950^0 C) does not make any indicative changes in Tensile Strength property of testing steel at given dimensions, if applied load, resulting stress and inducing strain deformation, is less than 500 MPa. But, if magnitude of the load inducing pressure more than 500 – 550 MPa, the strain deformation increases significantly. Diagram in Fig. 5 shows, that strain deformation (0.10 mm/mm) of grinded steel at 570 MPa increases twice, compare to reference material (0.05 mm/mm). Difference in Stress-Strain diagram related to the difference in dimensions of reference and machined specimens (3 mm), made by grinding process. Most likely, decreasing the dimension of the specimen, for the same type of steel (with same thermal conductivity), increases probability and amount of Strain deformation, but that is the subject of additional study.

To perform structural analysis we used the ESM to indicate noticeable changes on surface structure of machined material. All images of the surface for two (initial and machined) samples, shown below, were taken at three different increases: first – at 330x increases, that presented on Fig. 6, second – at 25000x increases (Fig. 7) and finally at 50000x increases (Fig. 8).

The sample of grinded steel shows more irregularities on the surface, and it is possible to show two different phases: one phase is more smooth and the another is apparently more rough. The smooth phase is very similar with the surface shown for the reference sample. However as was explained this characteristics of the materials also does not induced any deformation in testing items. Probably this structural differences apparently only are on the surface of the materials.

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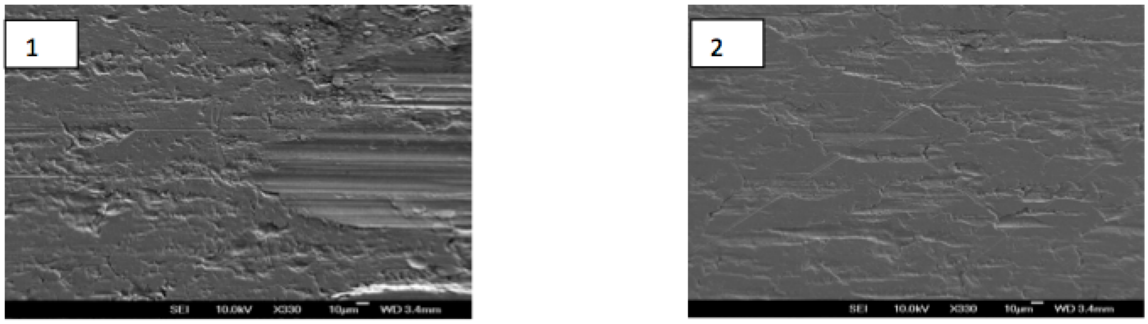

Fig. 6. SEM images of reference (1) and machined (2) B1112 steel taken at 330x increases.

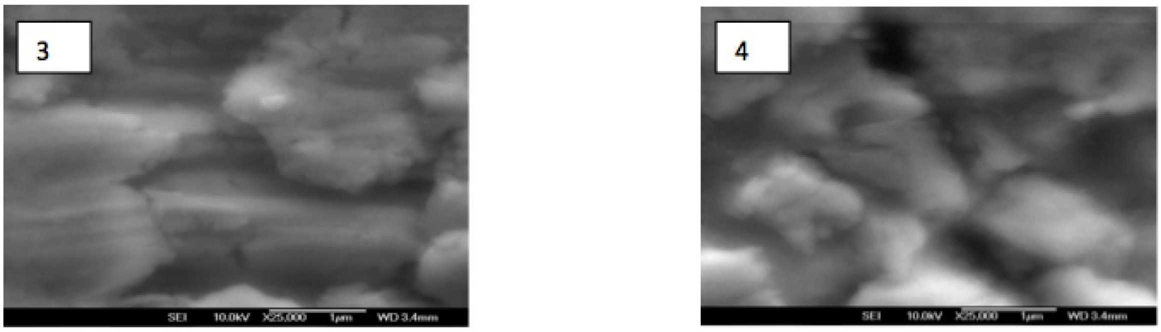

Fig. 7. SEM images of reference (3) and machined (4) B1112 steel taken at 25000x increases.

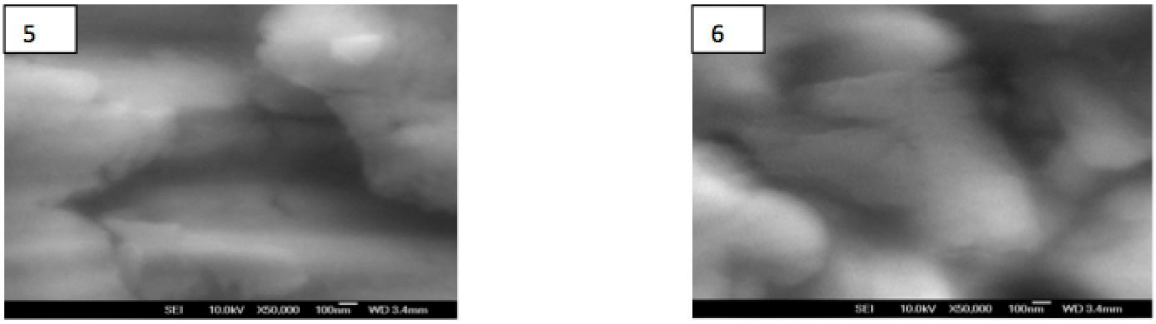

Fig. 8. SEM images of reference (5) and machined (6) B1112 steel taken at 50000x increases.

IV. CONCLUSIONS

Laboratory experiments were performed to investigate how the normal and increased (overloaded) machining parameters (Work-piece Speed (V_w) and Grinding Depth (d)) changes heat influence and some properties of material, and defined following:

1. The temperature in grinding zone (workpiece – abrasive wheel – chip) *significantly depends and increases* with increasing the Grinding Depth (mm) and not much, when escalating speed of work-piece (mm/sec), but temperature does not rises more than 950^o – 1000^o C at very high machining parameters, because great amount of heat dissipated with very fast forming and removing chip, preventing diffusion of the heat in work-piece.

2. Hardness is the state of the metal near the surface (we consider it as a surface property) does not have noticeable difference for the reference and machined specimens under the application of Load up to 1000 kg, and this difference less than 2 mm^2 of curved area, when temperature in cutting zone was less than 800^o C. The Hardness property of the testing steel degrades if the heat in machining process increases temperature in grinding zone more than 950^{0}C.

3. The thermal stress induced by high temperature in grinding zone (up to 950^0 C) does not make any significant changes in Tensile Strength property of testing steel at given dimensions, if applied load induced pressure less than 500 KPa. Strain appears, and makes significant deformation of testing elements, when stress rises over 550 MPa, but dynamics and character of the Strain deformations for both of testing specimens the same and almost identical.

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