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# Effect of Friction Machining on Low Carbon Steel with Titanium Traces in terms of Surface Hardening

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## Abstract

This work is an experimental study of thermo-mechanical surface hardening of mild steel with trace elements like titanium in negligible concentrations. This is somewhat an advanced technique used to harden steel surface which can be hardened in many typical ways. The concept is combining the thermal as well as mechanical technique to attain better results. It is quite obvious that mechanical refers to the compressive loading during machining and thermal refers to producing heat on the surface of work piece. The ideal conditions are when the heat produced is enough to achieve austenite and then subsequent quick cooling helps in the formation of martensite, which is metallurgically the most highly strong phase of steel, in terms of hardness. The coolant used preferably is the emulsified oil which flows on the surface during machining with variable rate of flow as the optimum effect is. This process hardens the surface of steel and increases its resistance against wear and abrasion. Preference is to achieve surface hardening using the conventional equipment so that operational cost is kept low and better results are attained. This technique has been quite successful in the laboratory. It can be termed as friction hardening. Some improvements in the process scheme and working environment can be made to get better results.

**Keywords:** Knee type vertical milling machine, High speed steel tool, Mild steel work piece, Thermo-mechanical face milling

## 1. Introduction

To establish background knowledge on the topic, the overview of conventional methods is important. These are three basically three types of methods with respect to the category of the processes in surface hardening of steels, i.e. thermal hardening, mechanical hardening, diffusion methods etc. It is vital to mark some of the known limitations of conventional methods of steel surface hardening. The foremost is high equipment cost alongside the high operation costs. Processing times are quite long and in many methods high accuracy equipment is needed. The production rates are retarded in some methods and some have radiation hazards too. The stated combination technique discards the diffusion methods and combines thermal and mechanical methods for a better output as projected in the theoretical findings. The experiment may also be attempted on non-ferrous metal specimens like aluminum for instance, in order to see whether the technique is broad based or not.

In mechanical methods the compressive stresses play the key role in surface hardening. In thermal methods the phase crystallization and grain refinement are of importance. The term austenitizing refers to heating the steel with room temperature phases to achieve a solid solution termed as austenite is fast but much more time is needed for carbon to spread everywhere to give uniform concentration; from cementite to austenite. Carbon is an interstitial solute which diffuses quickly in case of ferrite to cementite transformation; it still needs about twenty minutes, as stated cementite to austenite takes considerable longer. Further, on slow cooling, if austenite returns to room temperature, the equilibrium phases of ferrite and cementite are achieved. Cementite is rich in carbon and ferrite low. These two phases if present indicate the lack of coordination of parameters to achieve the best possible results. Rate of cooling has a visible effect or microstructure. Austenite is face centered cubic (FCC) but it is changed to body centered cubic (BCC). Quick cooling does not inhibit the transformation from Austenite to Ferrite but if does not allow carbon to spread in all directions in the lattice structure, so, it redistributes in one direction and the structure achieved is body centered tetragonal (BCT) called martensite. [1,2] Martensite is not a stable equilibrium phase so it is not visible on the iron carbon phase diagram. If reheated, the redistribution of the carbon atoms will give restoration of cementite once again. Martensite is the hardest phase because trapping and congestion of carbon atoms and unavailability of enough heat to allow carton to redistribute. This phase is quite hard but its use is on the surface only because too much hardness inside bulk material causes brittleness which causes easy fracture in materials. Hardenability of the steel is also important low critical cooling rate tends to achieve high hardenability so on not a fast quenching rate to avoid cracking, phases like martensite are achieved. In general, fast cooling rate gives better phase transformation as desired and better surface hardening. [3,4] Alloying elements in steel and austenite grain size can affect the hardenability of steel; finer austenite grain size gives low level of hardenability.

Some similar experiments have also been performed as a reference point on the aluminum samples to mark the application on non-ferrous metals also. In case of aluminum samples which have not been reported here, there has been less increase in the surface hardness and more disturbance on the surface due to material removal probably due to softness of the specimen material which makes such a process more suitable for friction drilling with a slightly different tool design without cutting edges which is another proven application of friction machining.

There are thermal stresses during machining and the possibility of overheating and slight melting at the tool-work piece interface has been observed which rather makes it a potential heat transfer problem in the heat affected zone of the work-piece. In such a case switching to the use of friction machining to melt and deform the subject metal can be more suitable to make holes in non-ferrous sheet metals like aluminum with a different tool geometry but strictly without cutting edges.

## 2. Methodology

In the stated thermo-mechanical steel surface hardening, friction is used to raise the spot temperatures in order to achieve the phase transformation and simultaneously the coolant is applied to achieve the hardest possible phase in theory known. The mechanical load serves its purpose of compression but extraordinary results need phase transformation to take place which needs high temperature, not only extreme stresses at the machining spot i.e. tool-work piece interface.[5] Surface machining using friction improves the surface finish and hardens it very well but only friction will increase the time of processing, so if not as much as ideally projected but to a considerable extent, phase transformation is needed. Ferrite and cementite are partly converted to austinite during optimum speed friction machining and along with quenching with the use of fast flow coolant, it is attempted that fast drop in temperature might possibly convert austinite to martensite as a theoretical projection.

Mechanical stresses during machine alongside the thermal stresses, and the rise and fall of temperature with high speed machining and fast coolant flow can give appreciable results atleast in the laboratory experiments.[6] Sample preparation for light microscopy is done under typical metallographic conditions. The steps of sample preparation for characterization of the specimens have been mainly grinding, polishing and etching for optical microscopy in the standard settings. Grinding is done with P60E paper, polishing with P400, P800, P1200 papers respectively and etching is done with nital for OM (optical microscopy) [7,8] Tools for long service life are made of very hard materials like tungsten carbide, depending on the budget and scale of application. The material of the tool is somewhat secondary in laboratory settings but preferably high speed steel, whatever choice is made, tool has to be harder than specimen and much more wear resistant as well as capable of taking machining stresses as compared to the work piece which could be a suitable grade of mild or low carbon steel suitable for experiments.

The experiments have been performed on mild steel samples with different compositions with and without titanium traces and results have been quite similar. The reason to report mild steel with titanium traces is due to the specimens procured from the steel casting industry from certain stages of the casting with typical inclusions and their expected influence on the surface properties. Both corrosion resistance and surface abrasion resistance in low to medium carbon steels are attributed to the presence of titanium in steel in the existing literature relating to the steel properties.

The use of coolant and the coolant flow rate during face milling can be a matter of choice. The rationale is that the faster the coolant is applied, the more is the phase transformation expected and the chances of producing martensite on the steel surface which is not probable but sometimes possible. The material characterization techniques used are not advance in this case so limited parameters have been used instead of aggressive machining. Also coolant flow is somewhat related to the conduction and convection modes of heat transfer which are more related to the machanical aspects of the problem.

Procurement has been made from Heavy Mechanical Complex Taxila. Conventional mechanical workshop apparatus with innovative machining is used to achieve the research goals. In this study, knee type vertical milling machine is used with a semi-cylindrical high speed steel tool and a flat surface mild steel work piece. There is a variety of tools that can be used but viability demands that high speed steel tool be used. The specimen subject to experiment could easily be any grade of mild steel with the stated trace elements like titanium. However, the used composition of the high speed steel tool and the mild steel work pieces are according to the manufacturer are in table 1:

Table 1.
Table of Compositions

| | Tool | Specimen 1 | Specimen 2 |
|---|---|---|---|
| Carbon | 0.99% | 0.17% | 0.19% |
| Silicon | - | 0.31% | 0.24% |
| Manganese | - | 0.71% | 0.74% |
| Sulphur | - | 0.03% | 0.04% |
| Tungsten | 5.97% | - | - |
| Chromium | 0.42% | - | - |
| Vanadium | 1.95% | - | - |
| Molybdenum | 4.95% | - | - |
| Titanium | - | 0.02% | 0.03% |
| Iron | Bal. | Bal. | Bal. |

The activity steps are as follows in figure 1 :

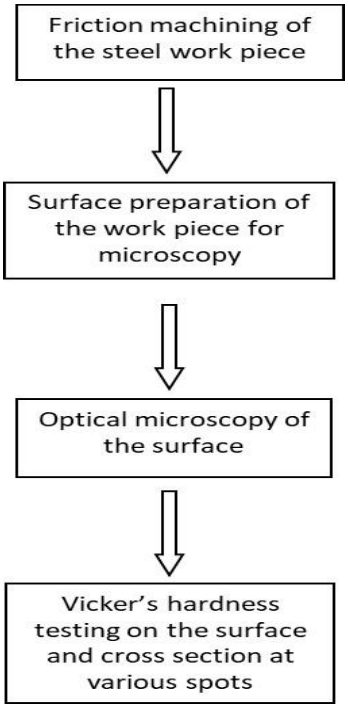

Fig. 1. Flowchart of the research activity

The scheme of operation of the tool and work piece interaction in the face milling process with a knee type vertical milling machine is given in figures 2a and 2b:

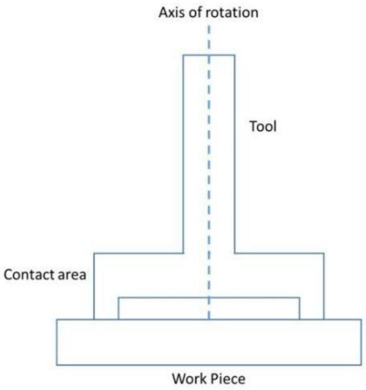

Fig. 2a. Process scheme of friction machining

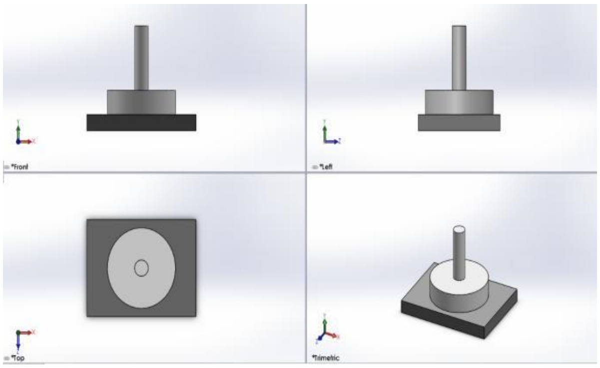

Fig. 2b. 3D models of friction machining process

## 2.1. Experimentation and Testing

Input variables of the machining will be RPM, feed rate, coolant flow rate, relative surface velocity of the tool, Vertical load on the specimen, number of passes and material of the tool tip. The output variables are surface finish, surface hardening and depth of hardened layer. [9] Experiment conditions for so called face milling operation for the stated work pieces are as in table 2&3:

Table 2.
Machining parameters for Specimen 1

| | |
|---|---|
| RPM | 1050 |
| Feed rate | 1.5 mm/rev |
| Depth of cut | 0.02 mm |
| Tool surface velocity | 225 m/min |

Table 3.
Machining parameters for Specimen 2

| | |
|---|---|
| RPM | 1250 |
| Feed rate | 2.5 mm/rev |
| Depth of cut | 0.05 mm |
| Tool surface velocity | 275 m/min |

The hardness test method chosen is Vickers and its machine variables are mainly vertical load and mean diametric of the indent. Metallography is also performed after the hardness tests, in order to identity the phases formed after machining. The main steps in metallography are sectioning, grinding, polishing and etching respectively. The results of microscopy are not very relevant because investigation has shown that the theoretically projected phase 'martensite' was not spotted, instead, much pearlite was there. Before and after machining of the work piece, Vickers hardness test have been done well below 1 kg load and the term implied is by definition micro-hardness. [10]

Vickers testing involves pyramid shape indentation of the surface specimen with a diamond indenter wherein the load is applied for a few seconds. The vertical load and the diagonal size of the indent are the key parameters in the calculation of surface hardness. It is important to be careful and not to indent near the edges and the corners of the specimen where there is error expected in the readings. However, multiple readings can be averaged out for a reasonable representation of the test result.

## 2.2. Surface Hardness Before and After Machining

Specimen 1 and 2 are both low carbon steels with slightly different amount of titanium inclusion traces. The error factor of these measurements is approximately five percent because many repetitions were made and consistent valued were picked for presentation. The tabulated data is presented below in table 4&5:

Table 4.
Specimen 1 surface hardness values

| Status | Indent 1 | Indent 2 | Indent 3 |
|---|---|---|---|
| Pre-machining | 271.2 | 246.2 | 274.3 |
| Post-machining | 618.9 | 547.4 | 568.3 |

Table 5.
Specimen 2 surface hardness values

| Status | Indent 1 | Indent 2 | Indent 3 |
|---|---|---|---|
| Pre-machining | 215.3 | 218.9 | 255.8 |
| Post-machining | 733.2 | 739.5 | 654.4 |

## 2.3. Cross-section Before and After Machining

Same procedure was repeated on the cross section to look for the depth achieved. The numbers are as follows in table 6&7:

Table 6.
Specimen 1 Cross-section hardness values

| Status | Indent 1 | Indent 2 |
|---|---|---|
| Pre-machining | 207.2 | 205.3 |
| Post-machining | 255.6 | 268.1 |

Table 7.
Specimen 2 Cross-section hardness values

| Status | Indent 1 | Indent 2 |
|---|---|---|
| Pre-machining | 191.1 | 197.3 |
| Post-machining | 277.9 | 281.3 |

## 2.4. Depth of Hardened Layer

As indicated there is depth in the surface hardness also which in technical terms is hardenability of the steel. The estimated values of it are given in the following table however the theoretical baseline was not fully met in the case of hardenability shown in table 8:

Table 8**.**
Hardenability approximation

| | |
|---|---|
| Specimen 1<br>Post-machining | 0.381mm |
| Specimen 2<br>Post-machining | 0.714mm |

## 2.5. Results in Graphical Form

Bar graph comparison on the main aspect of area of results is given in the following figure 3 with error less than five percent because of picking consistent date after repeated experiments:

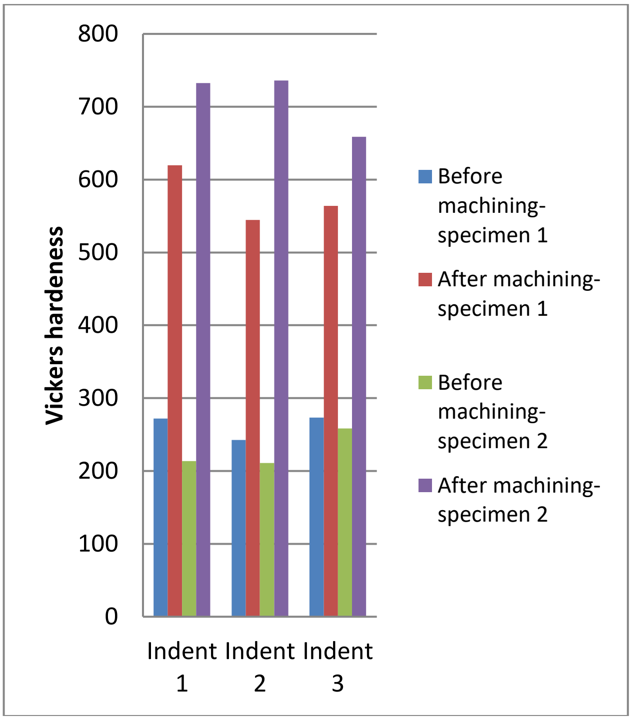

Fig. 3. Bar-chart comparison of surface hardness values with about 5% error

## 2.6. Light Microscopy

For optical microscopy only one sample is highlighted because there is not much difference in composition and machining parameters. The optical micrographs of the chosen sample are as follows in figure 4&5:

Fig. 4. Machined surface of specimen 1, 10x view

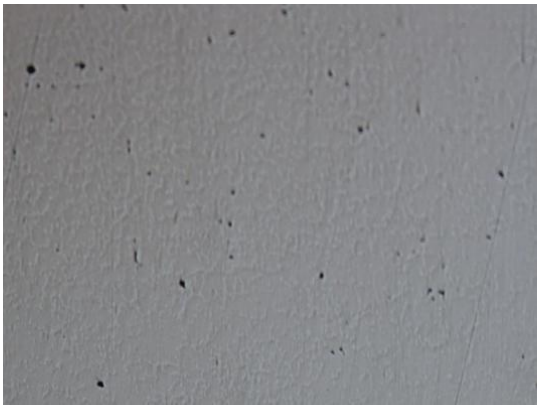

Fig. 5. Machined surface of specimen 2, 20x view

## 3. Results and discussion

The bars in the Vicker's hardness (HV) graph with baseline values about 200 HV rising up to 700 HV clearly indicate that there is considerable increase in surface hardening after the friction machining of the surface by the stated innovative method despite negligible amount of titanium inclusions in the mild steel. Also the hardenability values have shown to be 0.3 mm and 0.7 mm in two specimens used with slightly different amount of titanium traces showing a difference of about 100 HV pre and post machining. It goes without saying that friction machining does change the appearance of the surface which is depicted in the following optical micrographs at suitable low magnification. Two out of many specimens were chosen because theoretically assumed machining conditions were not applicable to the maximum potential for desired level of phase crystallization and the effect of titanium traces was small. Sample one and two have negligible and slightly different values of trace elements particularly titanium so the abrasion resistance is more related to machining than the composition itself.

It is of interest to mark the void of such a study, for instance, achievable hardening depth can be investigated further. Surface structure hardened can be categorized or more correctly characterized. Effect of mechanical loading on the microstructure evolution can be more specifically investigated. Surface performance can be evaluated in varied environments.

## 4. Conclusions

Friction hardening has proved itself to be effective as an innovative technique irrespective of trace elements like titanium inclusions in low carbon steel. The combination of both mechanical and thermal hardening techniques has a comparatively better result if compared to the results of one method only. The coexistence of thermal and mechanical stresses has enhanced the desired output. Vickers hardness tests have shown that even without the ideal phase transformation, the surface hardness has considerably improved. Surface finish is an obvious outcome of the friction machining and vertical load has shown that also better hardenability is possible with this combination technique.

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## Conflicts of Interest

There is no conflict of interests.

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