The Application of Temper-Etch Inspection to Micromilled AISI 4340 Steel Specimen

by

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ABSTRACT

Micromachining has seen application growth in a variety of industries requiring a miniaturization of the machining process. Machining at the micro level generates different cutter/workpiece interactions, generating more localized temperature spikes in the part/sample, as suggested by multiple studies. Temper-etch inspection is a non-destructive test used to identify ‘grind burns’ or localized over-heating in steel components.

This research investigated the application of temper-etch inspection to micromachined steel. The tests were performed on AISI 4340 steel samples. Finding, indications of localized over-heating was the primary focus of the experiment. In addition, change in condition between the original and post-machining hardness in the machined slot bottom was investigated.

The results revealed that, under the conditions of the experiment, no indications of localized over-heating were present. However, there was a change in hardness at the bottom of the machined slot compared to the rest of the sample. Further research is needed to test the applicability of temper-etch inspection to micromilled steel and to identify the source of the change in hardness.

ACKNOWLEDGMENTS

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INTRODUCTION

From the start of the industrial revolution, the manufacturing industry required larger tooling and machines. In the past ten years, there has been a new trend, shrinking the size of components for the medical, electronics and even the aerospace industry. Experimentation into micromachining dates back to the 1970's, but in the last ten years there has been significant growth. This growth is tied to improving technologies to respond to market trends for smaller gadgets, including medical instruments.

Statement of Purpose

The principal objective of this research was to determine if micromachining of AISI 4340 steel under various conditions would yield indications of localized over-heating by the use of temper-etch inspection. The secondary objective of this experiment was to determine if micromachining caused a change of hardness within the slot.

Factors such as chip load and depth of cut were investigated, while other factors such as surface speed and cutter wear were controlled for the experiment. The basis for the experiment is that the cutting forces in micromachining are different than in macromachining or conventional machining. As the depth of cut approaches the grain size, cutting forces transform from shearing to ploughing, thus increasing force and induction of heat into the surface.

Temper-Etch Inspection

Certain metal removal processes can induce enough heat into steels to change material properties in a localized area. This phenomenon, called localized over-heating, is broken into two types: localized over-tempering and localized rehardening. Industry typically refers to this phenomenon as ‘grind burns’ regardless if the cause is from grinding or some other mechanical removal method. The inspection process used to detect localized over-heating is temper-etch inspection and is governed by MIL-STD-867.

Essentially temper-etch inspection performs a non-destructive test of the surface integrity of a part or sample. Investigations of surface integrity have looked at microstructures or analytical models to describe the reactions at or just below the surface of the material. Although temper-etch inspection does not explain what is going on at the granular and microscopic levels, it does show that there is a heat induced loss of surface integrity.

The Design

The design of experiment will look at three factors at two levels. The three factors are:

1. Material hardness,
2. Chip load and,
3. Depth of cut.

This experiment yields eight test conditions that will be replicated six times for a total of 48 runs. The run order was randomly selected. To reduce the amount of material needed for the experiment, three slots were machined into each sample.

Anticipated Results

It was expected that the experiment would yield at least one indication of localized over-heating as part of the primary investigation. Some preliminary finite element analyses demonstrated an increased temperature due to inter-granular frictions.

It was expected that some evidence of increased hardness would be present. AISI 4340 steel typically exhibits work hardening in the tempered and hardened states (Matsumoto, Barash, Liu, 1986).

LITERATURE REVIEW

Currently, there is minimal research showing if there are effects on the metallurgical properties of medium carbon steels that have been micromilled. There are analytical models showing increased stress in the metals but they are limited to non-ferrous metals. However, there are no experimental data showing that increase in stress causes a metallurgical change in steel while machining under micro cutting conditions.

Since steel is a widely used engineering material, it is useful to know the effects of micromachining on the metallurgical properties of steel. The use of temper-etch inspection on micromilled hardened steels has not been used to determine if localized over-heating occurs.

AISI 4340 Steel

AISI 4340 steel is a low alloy steel known for its toughness and high strength in the heat treated condition. Typical uses for AISI 4340 are aircraft landing gears, and power transmission gears (http://www.suppliersonline.com).

According to Matweb, (http://www.Matweb.com) AISI 4340 steel has the following chemical elements:

Table 1: Element Percentage by Weight

Element	Percentage by weight
Carbon, C	.370-.430
Chromium, Cr	.700-.900
Iron, Fe	95.195-96.333
Manganese, Mn	.600-.800
Molybdenum, Mo	.200-.300
Nickel, Ni	1.650-2.000
Phosphorous, P	Less than .035
Silicon, Si	.150-.300
Sulfur, S	Less than .040

Steel such as AISI 4340 have as part of their grain structure martensite and austenite. Martensite is a body-centered tetragonal occurring in hardened steel (Budinski & Budinski, 2005). Austenite is a face-centered cubic, which is soft with moderate strength (Budinski et al., 2005).

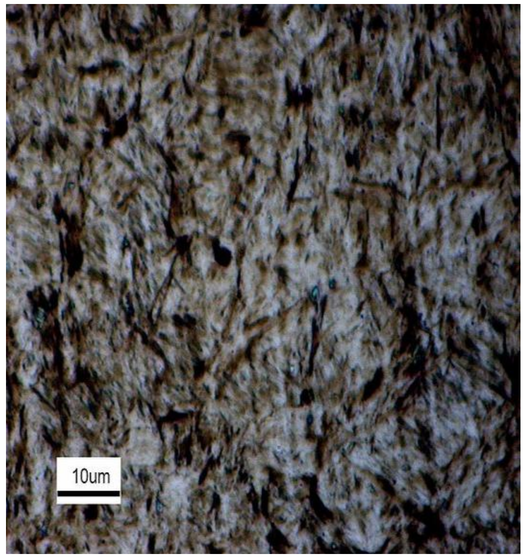

Figure 1: Martensite in AISI 4140 Steel

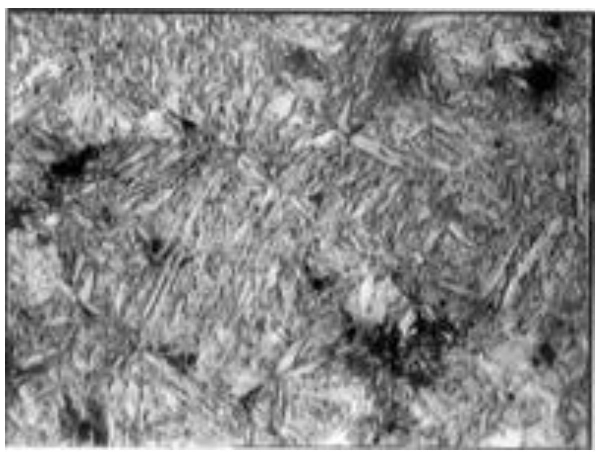

Figure 2: 0.35% Steel, Water Quenched

Figures 1 and 2 show typical micrographs steel (http://www.wikipedia.com).

Micromachining

Loosely defined, micromachining is material removal occurring when the cutter is operating at less than .25 of an inch. Micromachining has also been defined based on a set of cutting conditions where the uncut chip thickness is less than 999µm (.0393 inches) (Simoneau, Ng, & Elbestawi, 2006).

Modeling of micromachining conditions vary in comparison to macromachining. When depths of cut and feed rates are reduced the chip load encountered in the process becomes the same order of magnitude as the grain size of many alloys. In conventional machining the workpiece is thought to be homogeneous and isotropic. Modeling of micromilling, the workpiece is thought to be heterogeneous and anisotropic (Vogler, DeVor, Kapoor, 2003).

Micromachining has applications in the medical, aerospace, electronics and semi-conductor industries. Micromachining is used for manufacture of inserts for injection molding (Dimov, Pham, Ivanov, Popov, & Fansen, 2004). Micromilling is important to the manufacture of micro-parts for watches, housings for micro-engines, and tooling inserts for micro-filters (Popov, Dimov, Pham, Minev, Rosochowski, & Olejnik, 2006).

Minimum Chip Thickness

It has been found that there is a dramatic increase in shear energy as the uncut chip thickness decreases (Simoneau et al., 2006). This increase in energy may be directed into the part instead of into the chip in machining in the macro world. The stresses in the grain boundaries are addressed using a finite element analysis.

Figure 3 shows the initial conditions in the finite element analysis where materials A and B are rough approximation of pearlite and ferrite and the depth of cut is five micro meters (Simoneau et al., 2006).

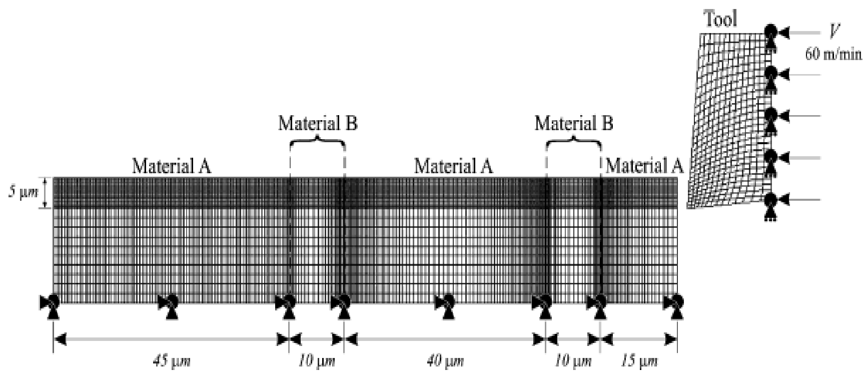

Figure 3: Finite Element Model Initial Condition

As the cutter engages the steel, grain A rolls up the cutter and rubs on grain B. As this occurs, the friction causes temperature increases shown as darker areas at the A-B grain boundary and the tool-chip interface as seen in Figures 4 and 5 (Simoneau et al., 2006).

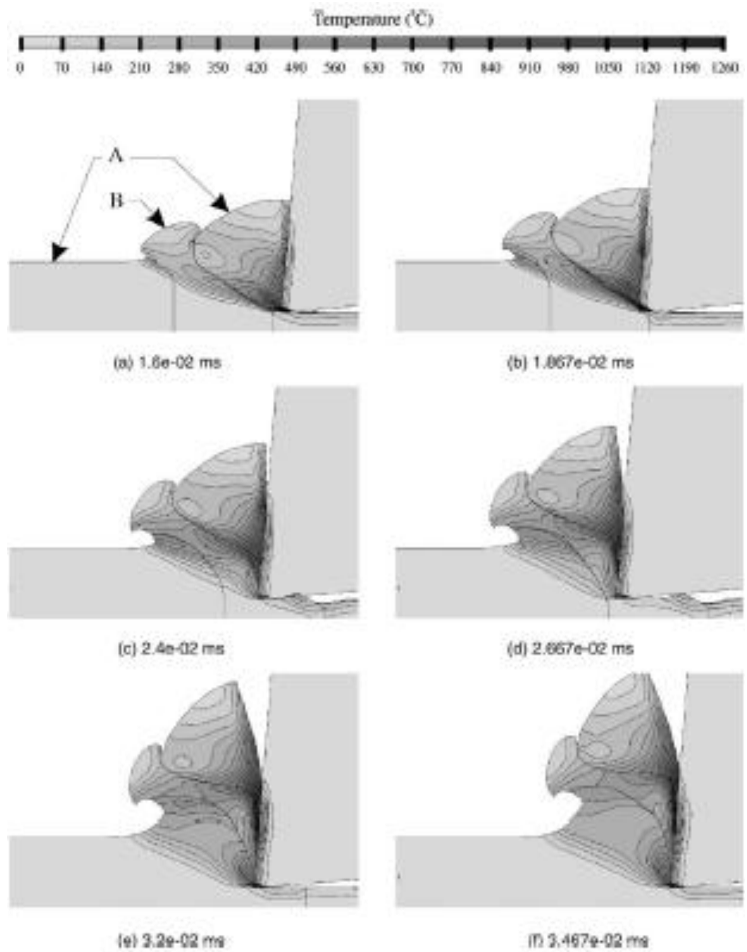

Figure 4: Temperature Rise Finite Element Model at Start of Cut.

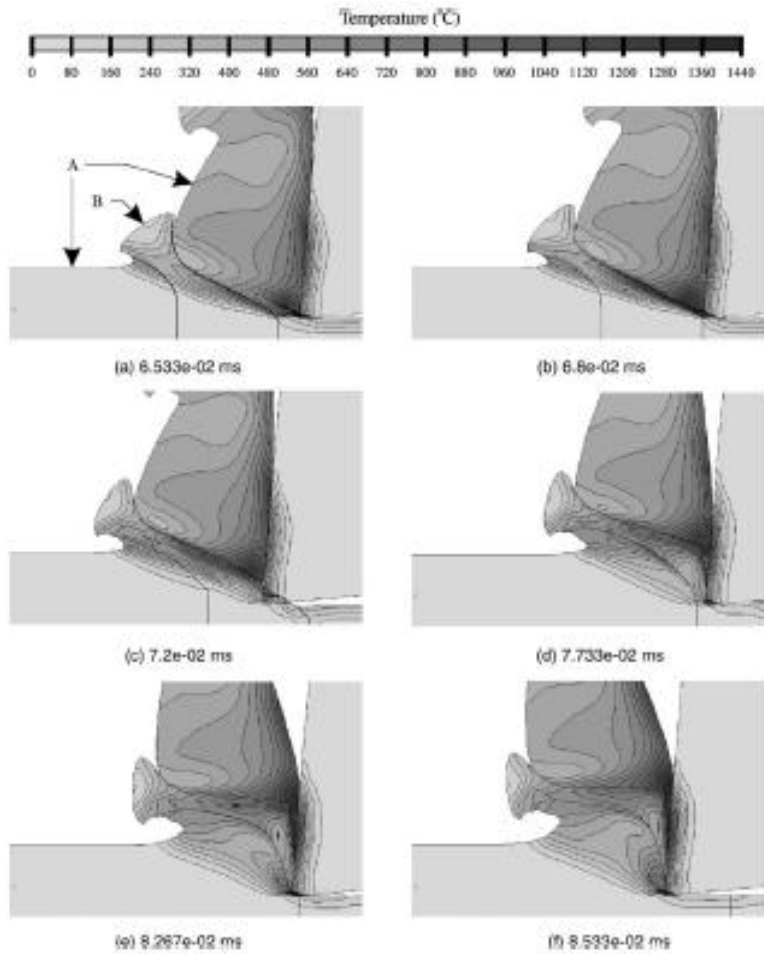

Figure 5: Temperature Rise Finite Element Model at Start of Grain Friction

Typically, as the temperature approaches the melting point of the material as in figures 4 and 5, the flow stress would approach zero. But, if the pressure from the cutting forces is high enough, this would prevent the flow stress from reaching zero and thus inducing more heat (Simoneau et al., 2006).

Chip formation in micromachining is primarily controlled by a phenomenon known as minimum chip thickness. Minimum chip thickness is also known as the minimum thickness of cut. In metal cutting the minimum thickness of cut is the minimum un-deformed thickness of a chip that can be removed stably from a work piece (Ikawa, Shimada, & Tanaka, 1992).

When making cuts below the minimum chip, cutting results from the radius of the tool. The radii on micro end mills have relatively large radii on the cutting edge when compared to conventional sized end mills. Since the cutting edge radius is not proportionally scaled down for micro end mills, the uncut chip thickness is smaller than the cutting edge radius and the chip forms in the area of the radius. This causes a high negative rake that is not present in larger end mills. Figure 6 highlights the main difference between macro and micro cutting. The relative bluntness of the tool increases the cutting forces. Above certain of edge radius to chip thickness ratio, expectation of a ploughing action is expected to dominate the cutting process (Bissacco, Hansen, & De Chiffre, 2005).

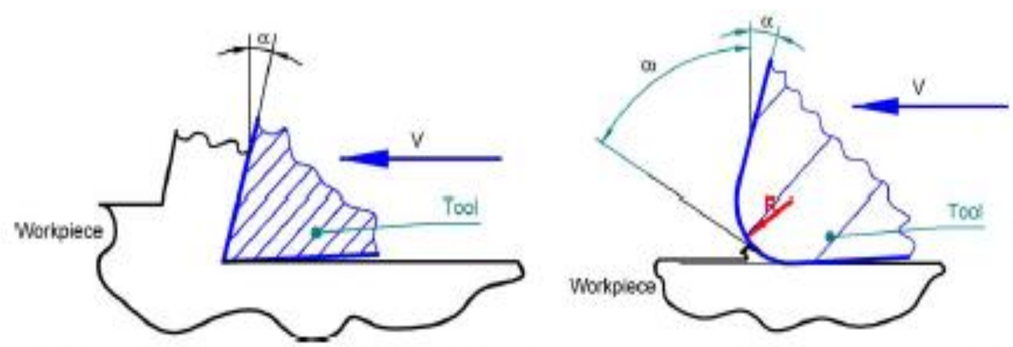

Figure 6: Macro Cutting Versus Micro Cutting (Bissacco et al., 2005)

The cutting parameters typically used in micromilling guide the material removal process to be dominated by the interfacial interaction involving the cutting edge and the work piece material (Popov et al., 2006).

In micromachining, the edge radius of the cutting tool is comparatively larger that the chip thickness, resulting in the cutting edge having a large negative rake angle. This affects the extent of the ploughing and shearing forces (Chae, Park, & Freiheit, 2006). Because of this a relatively large volume of material must become fully plastic for a small amount of material removal. This results in a considerable increase in energy. Chips may not form during this cutting process, but instead the work piece may elastically deform (Chae et al., 2006). The correlation between tool radius and minimum chip thickness is dependent on the cutting edge radius and the work piece material (Chae et al., 2006). Further, it was found that in general as the depth of cut is decreased the specific cutting energy will increase (Kim, Lee, Sin, 1998).

Komanduri's investigation to connect the relationship between negative rake machining and grinding concluded that high negative rakes and small depth of cuts, results in no chip formation with ploughing and the side spread of material. It was also found that plastic deformation occurs ahead of the tool tip and into the machined surface (Komanduri, 1971).

Specifically for AISI 4340 steel it was found that the minimum chip thickness is .35 µm (.0000137 inches) with a 400µm (.0157 inch) four flute end mill (Jinsheng, Dajian, & Yadong, 2009).

Surface Work Hardening

Surface integrity is defined as intrinsic or altered condition of a surface formed in a machining or other surface generating operation. The character of the surface layer has been discovered in many situations to have a strong influence on the mechanical properties of the part (Field, Kahles, 1968).

Machining as a process is characterized by high strain rates, high stresses, elevated temperatures and short interaction time with the workpiece as seen in Figure 7. This results in some changes at the surface such as micro-hardness changes, micro-structural changes and residual stresses. Generally the heat is conducted into the workpiece thus; local surface temperature can increase significantly (Chou, 2002).

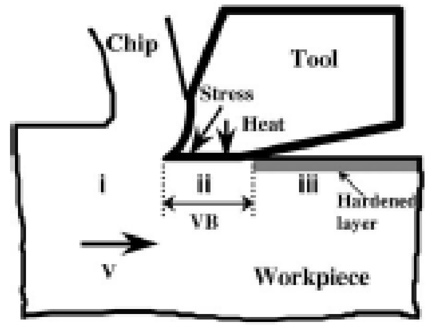

Figure 7: Thermomechanical Loading (Chou, 2002)

Compressive residual stresses always occur in thin layers at the surface caused by martensite transformation. Carbon content drives the size and variation of the residual stresses (Grum, 2001).

The quality of surfaces is driven by multiple factors including surface roughness, plastic deformation, residual stress, and structural changes. Three major sources of residual stress are mechanical deformation due the cutting edge, thermal stresses because of the heat produced by cutting, and volume change in the surface layer because of the structural changes. The pattern of residual stresses is dependent of the hardness of steel (Matsumoto, Da-Chun, 1987).

The following was discovered when looking at the surface condition:

- The hardness of steel alters the shape of the residual stress distribution under the machined surface.
- Untempered martensite can appear in certain conditions in very thin layers,
- Variations of residual stress pattern can be explained by mechanical deformation
- Thermal stress is secondary (Matsumoto, et al., 1987).

There are many different ways that the surface condition can be altered. During the process of grind hardening of steels, thermomechanical impact can cause alterations to the surface such as; cracks, tempered zones and white etching (Brockhoff, 1999).

MIL-STD-867, Temper-Etch Inspection and Surface Burns

Some performance characteristics that are sensitive to surface integrity are; fracture strength, fatigue strength, corrosion rate, and dimensional stability. Metallurgical damage related to high surface temperature can be defined by:

- untempered martensite
- overtempered martensite
- oxidation
- decarburization
- superficial microcracks

These are commonly lumped together under the general industry term “grind burns.” Figure 8 shows for a given percentage of carbon, when martensitic transformation begins (Shaw, Vyas, 1993). The M_s line is the temperature at a given level of carbon that martensitic transformation starts.

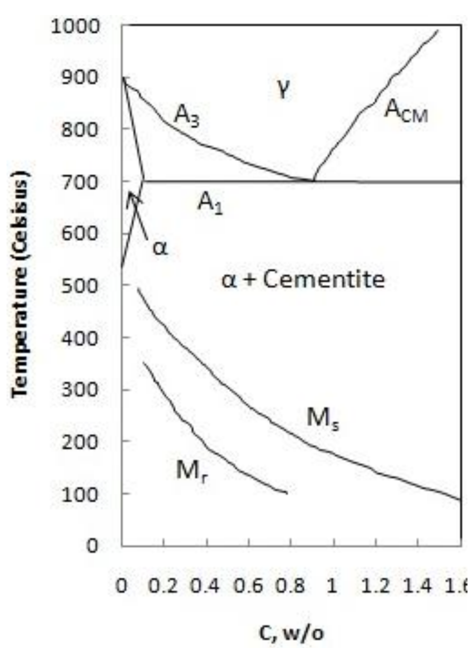

Figure 8: Equilibrium Phase Diagram for Fe-C

Surface burning appears to be a property of iron as a component of steel. It can be seen from the iron-carbon diagram that, the only constant independent of alloying is the eutectoid temperature. Surface burns are possible anytime material removal exceeds the eutectoid temperature in annealed steels. In hardened steels, this can occur at temperatures as low as 150 Celsius depending on the alloying elements (Ali, Zhang, 2003).

High temperatures at the work surface such as in grinding cause several quality issues such as residual tensile stress, surface burns and reduced fatigue life. Burning is expected at approximately 720 Celsius and re-hardening is expected at about 860 Celsius (Devia, Vijayaraghavan, Krishnamurthy, 1999).

Workpiece burn is accompanied by re-austenitization at the surface layers. Etching of the surface will expose the martensitic layer as a white phase (Devia et al., 1999).

High temperatures can cause various types of thermal damage to a workpiece; burning phase transformation, tempering of surface layer with rehardening, residual stresses, cracks and lowered fatigue strength (Malkin, Guo, 2007).

The principle of temper-etch inspection is to test if sufficient heat has been induced after the final heat treat. This induced heat is applied by various material removal methods and could adversely affect the properties of the workpiece. Acceptable workpieces will have a uniform gray color (United States Air Force, Department of Defense, 2008). Unacceptable workpieces that show indications of untempered martensite will be indicated as white or light gray, while over tempering will be indicated by dark gray or black areas (Bailey, 1982).

METHODOLOGY

The primary objective of this investigation is to determine if micromachining of AISI 4340 steel in various conditions would yield indications via temper-etch inspection. There are many factors, which affect the induction of heat into the machining process. Factors such as material hardness, chip load and depth of cut will be investigated, while surface speed and cut time on the cutter will be controlled. The essential idea of the experiment is that micromachining cutting forces are different than in macromachining cutting forces. As the depth of cut approach the grain sizes, the forces change from shearing to ploughing, thus increasing force and induction of heat. The induction of heat into steel part is a concern during machining and grinding operation. The application of temper-etch inspection has been widely used in the application of detecting localized over-heating.

The secondary objective of this experiment is to establish if the micromachining process causes a change in hardness within the slot area. This will be tested by comparing the hardness of the slot bottom to the original hardness of the samples.

Significant amount of preliminary testing was performed to determine the parameters of the experiment. The early attempts to machine hardened steel with a .03 inch end mill ended in failure to complete a cut. The standard cutting parameters found in machinist guides for cutting steel do not apply to the micro cutting world due to the relative weakness of the smaller cutters. Ultimately a .06 inch end mill was selected and successfully cut a wide range of parameters.

It was determined early, that the material would be AISI 4340 steel at two different hardness levels. AISI 4340 was selected for its applicability in many industries and as a material that can show effects from localized over-heating.

Chip load and depth of cut were selected as other factors for the design, but the levels were dependent on the range of the parameters discovered while running the preliminary test with the .06 inch end mill.

The experiment will be carried out using AISI 4340 carbon steel in five primary phases:

1. Heat Treatment of the steel with various hardness levels,
2. Machining of the samples,
3. Temper-etch inspection,
4. Recording of data,
5. Data analysis.

AISI 4340 is a low alloy medium carbon steel. AISI 4340 consists of .400% carbon, .800% Chromium, .700% Manganese, .250% Molybdenum, 1.830% Nickel, Maximum .0350% Phosphorous, Maximum .040% Sulfur, .230% Silicon and the balance of weight in Iron.

The experiment was run using a HAAS Office Mill and it took five hours two minutes to complete the experiment. The first sample was loaded into the vise using a stop to set the part in the X-axis. The origin was set at the left end of the part for the X-axis and on the centerline for the Y-axis. All eight programs were created on Surfcam Velocity 4.0 CAM Software, using the same origin as described above. The Z offset was set for each sample to minimize the possibility of improper loading in the vise, which could lead to a tool crash or heavier first cut than expected. The warm up cycle was run prior to running the first sample. The program was changed each time to match the sample number and ran as programmed.

Experimental Design

Three variables were used in the experiment. The experimental design was a 2^3 design with six replications with the factors being hardness, chip load and depth of cut. Factor A was the hardness of the sample; with the upper level being 46-52 Rockwell C scale and the lower level being 38-44 Rockwell C scale. Factor B was the chip load with the upper level being 0.00098 inch and the lower level being 0.00039 inch. Factor C was the depth of cut with the upper level as 0.001 inch and the lower level as 0.0003 inch.

The controls on the experiment were material type, cutter size, slot depth, spindle speed and coolant use.

The material used was AISI 4340 Steel heat treated as required. The cutter size will be .06 inch four flute end mill. The slot depth was .01 inch. The spindle speed was locked in at 6400 revolutions per minute which equates to a surface speed of approximate surface speed of 100. The samples were assigned a code that will identify the sample to its factors. Samples one through four were factor A at the high level and five through eight at the low level of factor A. Samples one, two, five, and seven were at the high level of factor B and three, four, six and eight at the low level of factor B. Samples one, three, five and six were at the high level for factor C and two, four, seven and eight at the low level of factor C. Each sample had three slots machined on it requiring A and B versions of each sample. Table 2 highlights the treatment conditions.

Table 2: Treatment Conditions

	Treatment	I	A	B	C	AB	AC	BC	ABC
1	abc	+	+	+	+	+	+	+	+
2	ab	+	+	+	-	+	-	-	-
3	ac	+	+	-	+	-	+	-	-
4	a	+	+	-	-	-	-	+	+
5	bc	+	-	+	+	-	-	+	-
6	c	+	-	-	+	+	-	-	+
7	b	+	-	+	-	-	+	-	+
8	1	+	-	-	-	+	+	+	-

The samples were stamped with one through eight and the letters A or B. Then, each sample was stamped on the diameter to denote which occurrence on that sample it was, ‘I’ is for slot position one, ‘II’ is for slot position two and ‘III’ is for slot position three.

For the run order refer to Appendix A.

Heat Treatment

Heat treatment of the samples was completed in two recipe groups based on the Iron-Carbon Phase diagram in Figure 9 (http://www.wikipedia.com). The samples were heat treated to get the desired hardness. The A positive condition samples one, two, three, and four were heat treated to 1500 Fahrenheit and then, soaked for an hour, then immediately oil quenched until cool.

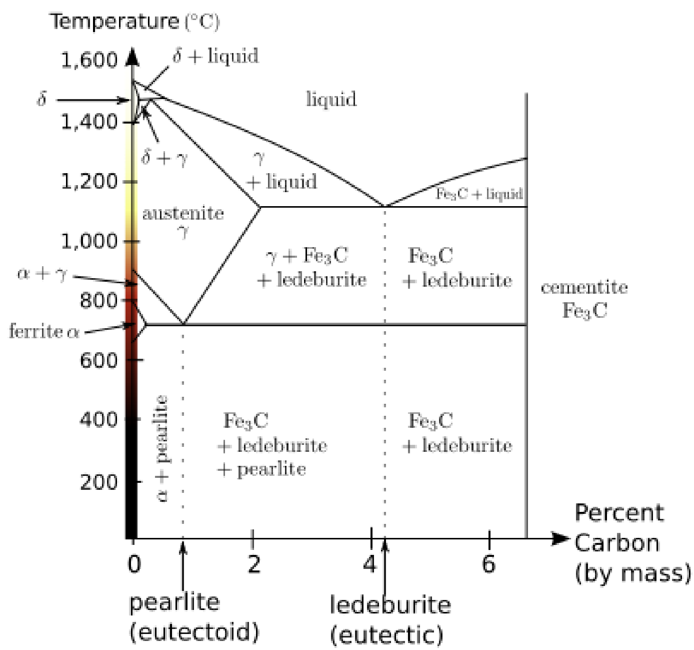

Figure 9: Iron-Carbon Phase Diagram

The A negative condition samples five, six, seven and eight were heat treated to 1500 Fahrenheit for one hour, cooled in oven to 900 degrees, then one minute air quenched and then quenched in oil until cool.

The samples were then, grit blasted to remove carbon deposits on the surface. Then, the samples were tested for hardness on a Rockwell hardness tester with a minimum of three times per sample to verify hardness.

Machining the Samples

Next, the samples were ground with no coolant on an outside diameter grinder allowing for the best chance to cause localized over-heating. This was used to compare micromachining to grinding a typical method for localized over-heating to occur.

Figure 10: View of Machined Slot End View

Figure 11: View of Machined Slot Top View

A .625 inch long pocket .01 inches deep was milled using a .06 inch diameter end mill into each of the samples as shown in Figure 10 and 11.

Programs were changed accordingly to match with the conditions setup under the designed experiment.

The 4 flute .06 inch end mill was changed every three parts to eliminate or minimize tool wear as an effect on the experiment in addition to randomization of the experiment. Figure 12 shows an example of the 4 flute .06 inch end mill used in the experiment.

Figure 12: 0.06 Inch, 4 Flute End Mill

Temper-Etch Inspection

Temper-etch inspection was completed per MIL-STD-867C. Per MIL-STD-867C, 4340 steel is a Group A and was etched as follows:

- Cleaned in a soapy solution at 134 Fahrenheit for fifteen minutes then rinsed and dried.
- The samples were agitated in 3.48% nitric acid by volume in water for seven seconds and then rinsed in ambient de-ionized water.
- The samples were agitated in 4.65% hydrochloric acid by volume in alcohol for thirty-five seconds and then rinsed in ambient de-ionized water.
- The samples were soaked in 10 pH soda ash solution for fifteen seconds and rinsed in 162 Fahrenheit de-ionized water.
- The samples were air dried and then dipped in anti rust oil.
- An inspection of the samples was completed under a lamp that produced 205 foot candles.

Subsequent Inspections

As part of the secondary objective, the slots were inspected for hardness at the bottom of the slot to determine if there was any change in the hardness of the samples. This inspection was completed on the same Rockwell hardness tester on the C scale, taking three measurements per slot for all slots.

Two samples 3A and 8A were cut to expose the grain structure in the core area and immediately under the bottom of the machined slot. One sample was selected from each hardness condition to examine the grain structures in each condition.

The cut samples were suspended in phenolic resin to holding the sample as to expose the desired surface. The samples were polished using a progression of coarse 220 grit abrasive paper with coolant to fine 600 grit abrasive paper with coolant. The samples were then polished, using coarse 9.5 micron aluminum oxide mixed in de-ionized water progressing to .3 micron fine aluminum oxide mixed in de-ionized water. Once the surface had a mirror surface, it was etched using a ten percent solution of nitric acid to expose the grain structure for inspection under a microscope.

The samples had micrographs taken of the grain structure in the core area and area under a machined slot using a high power microscope with a camera attached. The micrographs were used to reveal if there are any grain changes between the two areas.

DATA ANALYSIS

Initial Sample Hardness

For samples one through four, the average sample hardness as shown in Table 3.

Table 3: Sample 1a through 4b, Average Hardness

Sample	Average Hardness
1a	48.33
1b	49.67
2a	47.33
2b	47
3a	47
3b	48.67
4a	48.67
4b	50.33

For samples one through four, the average was 48.375 Rockwell C with a standard deviation of 1.527. The standard deviation is a measurement of the variation from the average.

For samples five through eight, average sample hardness as follows in Table 4.

Table 4: Sample 5a through 8b, Average Hardness

Sample	Average Hardness
5a	39
5b	41.33
6a	40.67
6b	40.33
7a	39
7b	41.67
8a	41.67
8b	40

For samples five through eight, the average hardness was 40.458 Rockwell C with a standard deviation of 1.25. The complete table of data can be found in Appendix B.

Primary Findings

The temper-etch inspections of all 48 slots yielded no indication of localized over-tempering or localized rehardening. Also, the ground test section of the samples did not show any indications of localized over-tempering or localized rehardening. Figure 13 and 14 show that no indications are present, this is indicative of the rest of the samples. In Figure 14, the dark spot in the center of the slot is a tool mark with remnant smut maintained in the tool mark after the temper-etch inspection.

Figure 13: Sample 1a After Temper-Etch Inspection

Figure 14: Sample 6b After Temper-Etch Inspection

Secondary Findings

Each slot was inspected for hardness three times per slot on a Rockwell hardness tester after calibrated to a hardness sample provided with the tester. Sample hardness in an un-machined area was verified to the original data prior to the inspection of the slot hardness. The original data set is available in Appendix B. The averaged sample readings as follows in Table 5:

Table 5: Slot Average Hardness

Slot	Average Hardness	Slot	Average Hardness
1aI	50.33	**5aI**	49.33
1aII	53.67	**5aII**	48.33
1aIII	51.00	**5aIII**	48.00
1bI	53.33	**5bI**	50.67
1bII	53.67	**5bII**	48.33
1bIII	53.67	**5bIII**	49.33
2aI	53.33	**6aI**	50.67
2aII	54.33	**6aII**	46.67
2aIII	53.00	**6aIII**	49.67
2bI	53.00	**6bI**	50.33
2bII	51.00	**6bII**	47.33
2bIII	52.67	**6bIII**	51.00
3aI	54.33	**7aI**	47.33
3aI	53.00	**7aII**	48.67
3aI	53.67	**7aIII**	48.67
3bI	54.33	**7bI**	48.33
3bII	53.00	**7bII**	48.00
3bIII	51.67	**7bIII**	50.33
4aI	54.33	**8aI**	50.33
4aII	52.00	**8aII**	48.67
4aIII	53.33	**8aIII**	49.00
4bI	50.00	**8bI**	47.00
4bII	52.67	**8bII**	48.33
4bIII	53.67	**8bIII**	47.67

A complete data set can be found in Appendix C.

The design of experiment was altered to use the same treatments but addressed slot hardness instead of the presence of localized over-heating.

- Factor A: hardness of the sample; with the upper level being 46-52 Rockwell C scale and the lower level being 38-44 Rockwell C scale.
- Factor B: chip load; with the upper level being 0.00098 inch and the lower level being 0.00039 inch.
- Factor C: depth of cut; with the upper level as 0.001 inch and the lower level as 0.0003 inch.

Factor A was found to be statistically significant with P values less than .05. Factors B and C and all interactions were found to be statistically insignificant with P values over .05. Data from the design of experiment can be found in Appendix D.

Results from the one sample T-tests for each of the treatments, used to verify if the mean hardness of the sample and the slot hardness were from the same population are shown in Table 6. The null hypothesis H_0: states that the sample hardness and slot hardness averages are statistically from the same population. The alternative hypothesis H_1: states that the sample hardness and slot hardness averages are statistically from different populations (H_0: $\mu_{sample\ hardness} = \mu_{slot\ hardness}$ H_1: $\mu_{sample\ hardness} \neq \mu_{slot\ hardness}$).

Table 6: Treatment levels, α level and p- value

Treatment	α level	p- value
1	.05	0.000
2	.05	0.000
3	.05	0.000
4	.05	0.000
5	.05	0.000
6	.05	0.000
7	.05	0.000
8	.05	0.000

Data from each one sample T-tests are in Appendix E.

Micrographs

Micrographs of samples 3a and 8a were taken at 50 times magnification and 100 times magnification in the slot and in the core of the sample to highlight if any changes in the grain structure are visible, as seen by Figures 15 through 22 and will be discussed further in the Discussion chapter.

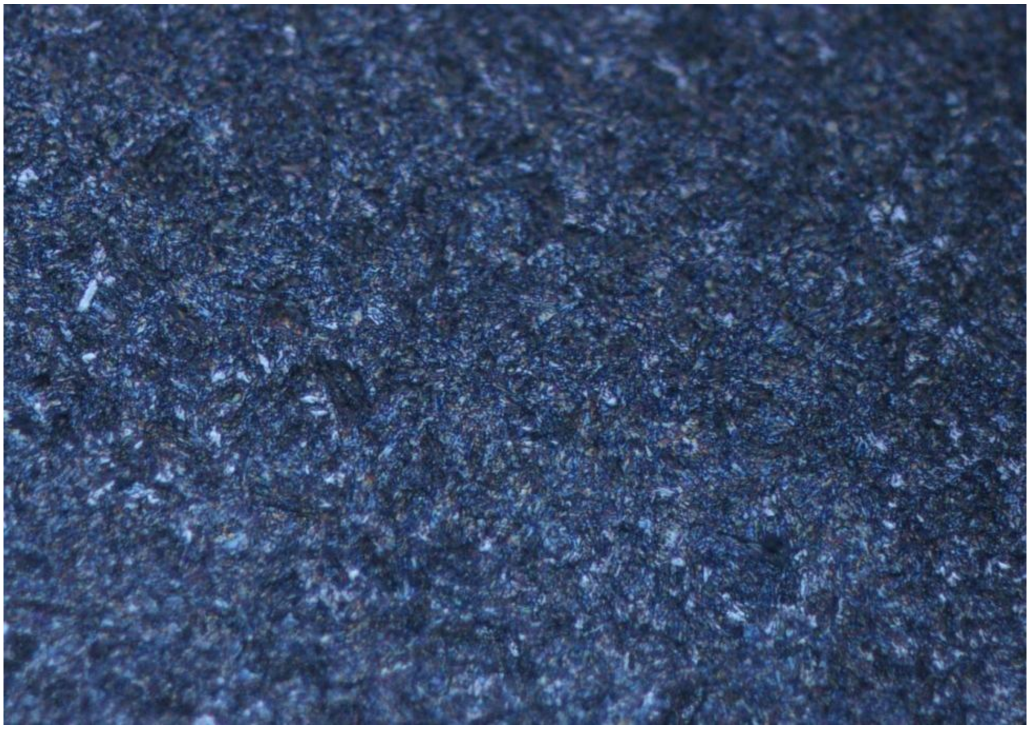

Figure 15: Sample 3a at 50 Times Magnification of the Core

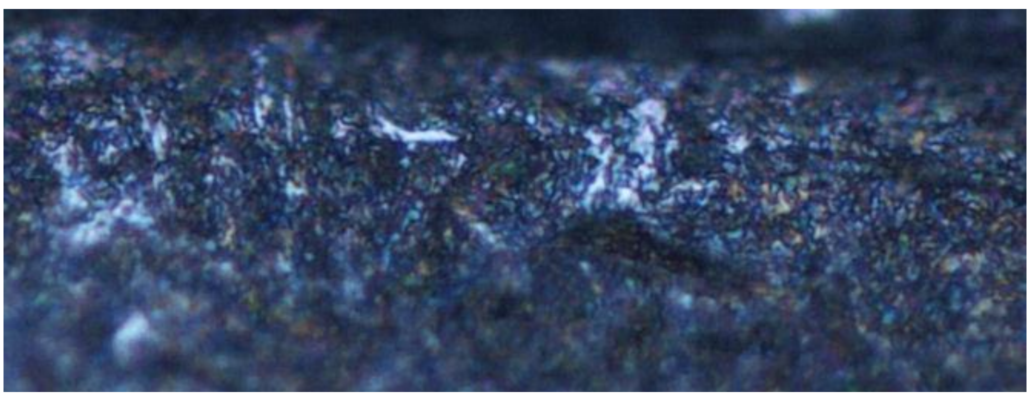

Figure 16: Sample 3a at 50 Times Magnification of the Slot

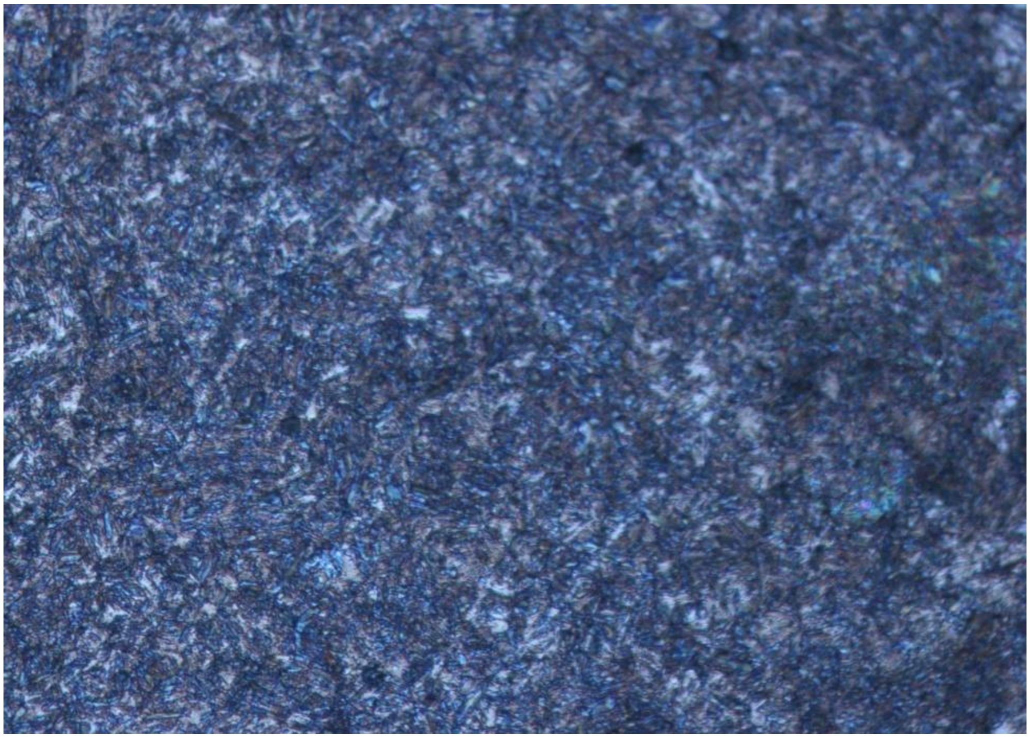

Figure 17: Sample 8a at 50 Times Magnification of the Core

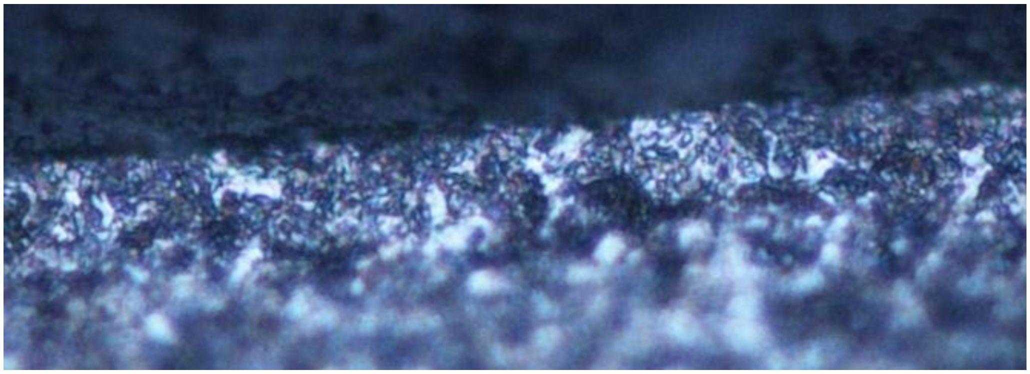

Figure 18: Sample 8a at 50 times Magnification of the Slot

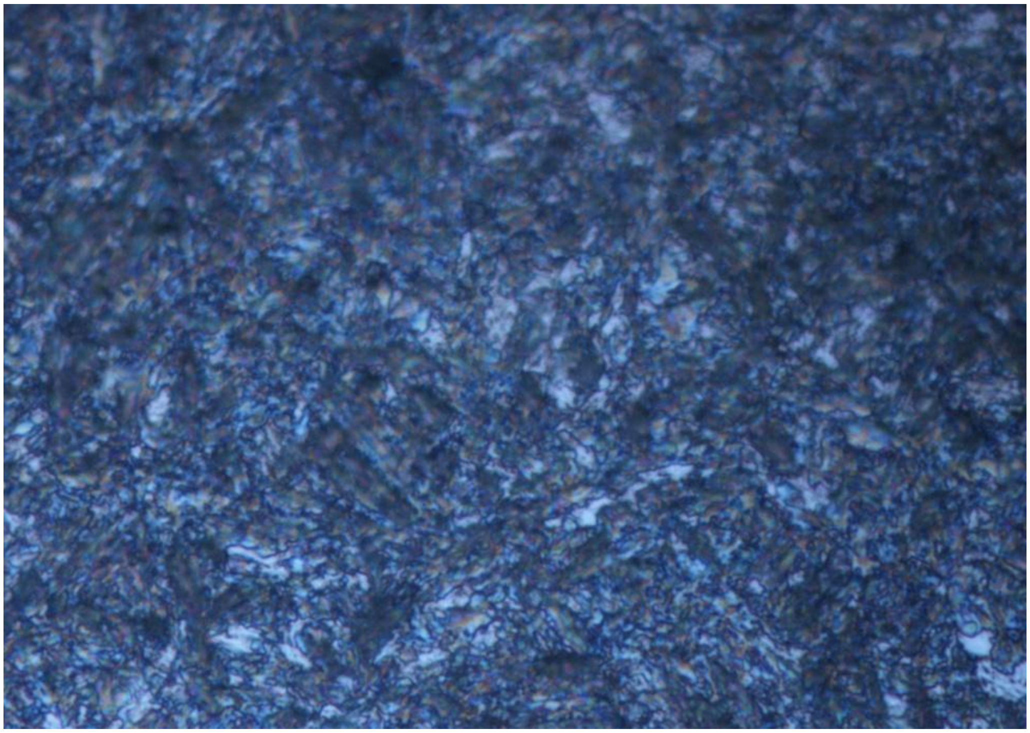

Figure 19: Sample 3a at 100 Times Magnification of the Core

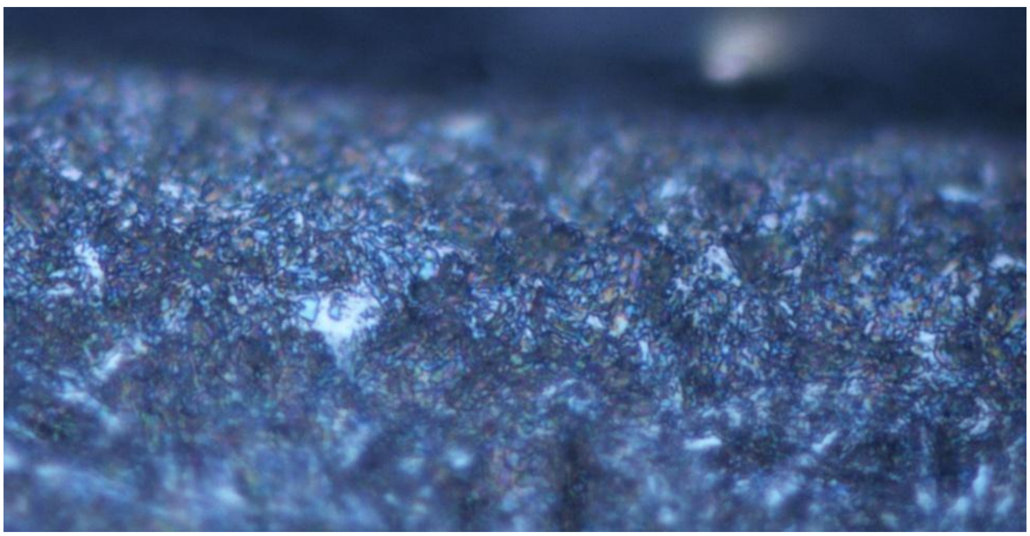

Figure 20: Sample 3a at 100 Times Magnification of the Slot

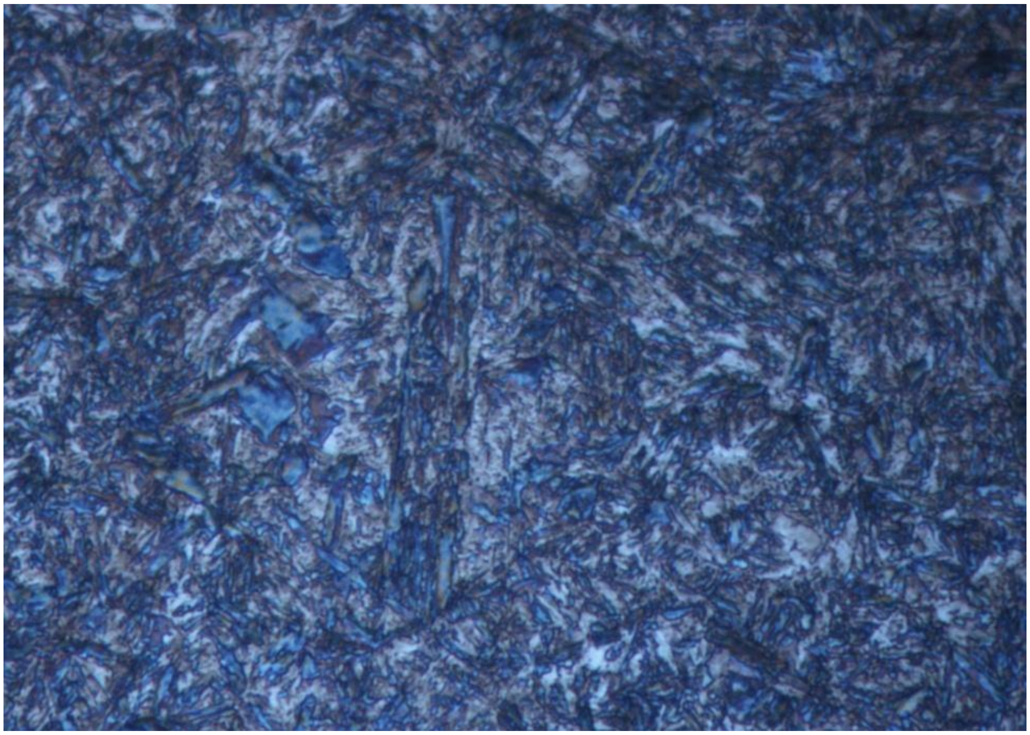

Figure 21: Sample 8a at 100 Times Magnification of the Core

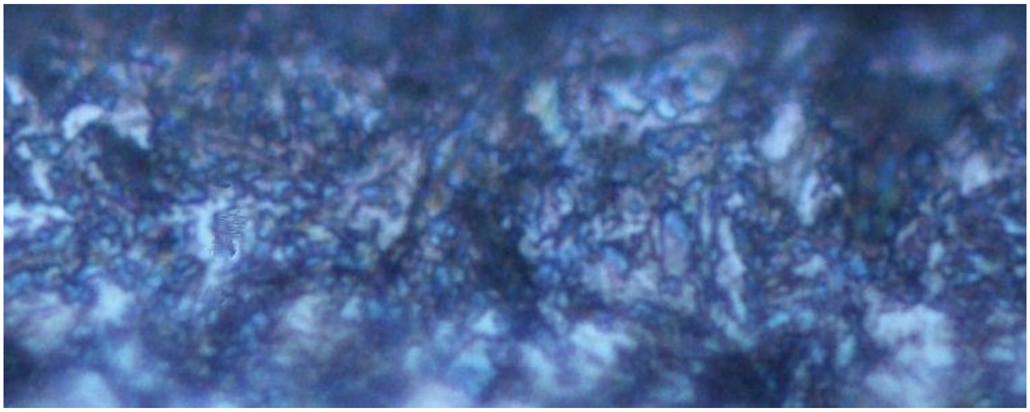

Figure 22: Sample 8a at 100 Times Magnification of the Slot

DISCUSSION

Interpretation of Findings: Primary Objective

The principal objective of this experiment was to determine if micromachining of AISI 4340 steel, under the conditions of the designed experiment, would yield localized over-heating, indicated by the use of temper-etch inspection. It was expected that at least one indication of localized over-heating would appear. The factors of the designed experiment were as follows.

- Factor A: hardness of the sample; with the upper level being 46-52 Rockwell C scale and the lower level being 38-44 Rockwell C scale.
- Factor B: chip load; with the upper level being 0.00098 inch and the lower level being 0.00039 inch.
- Factor C: depth of cut; with the upper level as 0.001 inch and the lower level as 0.0003 inch.

In all 48 slots, there were no indications of localized over-heating present, by means of temper-etch inspection. At the conditions of the experiment, there was not enough heat induced into the samples to alter the condition at the surface, contrary to expectations.

Interpretation of Findings: Secondary Objective

The secondary objective of this experiment was to determine if micromachining would cause a change in hardness within the machined slot. It was expected that a change in hardness would be present in the machined slot area.

All of the machined slots showed a change in hardness from the original condition. This is supported by one sample T-tests for each of the treatments, comparing the mean hardness for the samples and machined slot hardness. The null hypothesis H_0, tests that the means are equal and the alternative hypothesis H_1, tests that the means are not equal (H_0: $\mu_{\text{sample hardness}}=\mu_{\text{slot hardness}}$ H_1: $\mu_{\text{sample hardness}}\neq\mu_{\text{slot hardness}}$).

All eight tests yielded a p-value of 0.000, thus the null hypothesis is rejected and the alternative hypothesis is accepted. It appears that the change in hardness was due to either thermal induction or work hardening. Which of these mechanisms cannot be conclusively concluded based on the current data. The change in hardness was greater for the softer condition (5A) than for the harder condition (1A). This was true for all of the samples.

Factor A; sample hardness, was found to be statistically significant with regard to the hardness, with P values less than .05. This is expected due to the slot hardness dependency on the original sample hardness and that the change is based off of the sample hardness.

The factors B; chip load, and C; depth of cut, and all interactions were found to be statistically insignificant with P values over .05. Thus, factors B and C do not have an effect on the post-machining hardness. Data from the design of experiment are found in Appendix D.

Micrographs

The 50 times power and 100 times power micrographs of samples 3A and 8A show no appreciable difference in the grain structure between the core and slot areas. Thus, there is evidence of work hardening. The grain structures of all of the samples show a martensitic structure expected of samples in their hardness conditions.

CONCLUSIONS

Conclusions

This research investigated the application of temper-etch inspection to micromilling of AISI 4340 steel. The research compared various conditions of the steel and cutting parameters; sample hardness, feed per tooth and depth of cut. Two important objectives of the research were determined to test if temper-etch inspection revealed if localized over-heating occurred in micromachined 4340 steel and to test if there is an increase in hardness in the machined slots.

Temper-etch inspection of the samples did not yield any indication of localized over-heating. Therefore, it was not concluded that there was not enough heat induced under the machining conditions of this research to alter the properties of the steel.

The micromachining process did cause a change in slot hardness as compared to the original material hardness, verified by one sample T-tests. Since, localized over-heating was not detected by temper-etch inspection, it is suspected that the increased material hardness was due to work hardening. Statistical analysis yielded that the only significant factor was sample hardness. Since, sample hardness was the only significant factor, it was concluded that all other factors and their interactions would not yield significant changes to the slot hardness.

Recommendations for Future Research

Further research into different machining conditions and other types of steels is needed to determine if temper-etch inspection is an applicable non-destructive test to micromachining of steel.

This research also, suggested that only original sample hardness has an effect on the slot hardness. The chip load and depth of cut and all factor interactions had no effect on the slot hardness. Further research is needed to determine micromachining conditions that induce higher hardness at the machined surface. The cause of the change in hardness will need to be determined if it is a product of the process or the material.

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APPENDICIES

APPENDIX A: DOE ORDER OF RUN AND TOOL USAGE

APPENDIX B: SAMPLE HARDNESS

APPENDIX C: SLOT HARDNESS

APPENDIX D: FACTORIAL FIT: SLOT AVERAGE VERSUS A, B, C

APPENDIX E: ONE SAMPLE T TESTS

APPENDIX A

DOE ORDER OF RUN AND TOOL USAGE

DOE Order of run					
Run	**Program Number**	**Sample**	**Program**	**Slot**	**Tool Used**
1	7	a	7	I	1
2	1	a	1	I	1
3	4	a	4	I	1
4	7	b	7	I	2
5	2	a	2	I	2
6	7	b	7	II	2
7	5	a	5	I	3
8	8	b	8	I	3
9	6	a	6	I	3
10	3	a	3	I	4
11	5	b	5	I	4
12	4	b	4	I	4
13	3	b	3	I	5
14	7	a	7	II	5
15	5	b	5	II	5
16	8	a	8	I	6
17	8	b	8	II	6
18	5	a	5	II	6
19	3	b	3	II	7
20	2	b	2	I	7
21	6	b	6	I	7
22	2	a	2	II	8
23	6	a	6	II	8
24	3	a	3	II	8
25	8	a	8	II	9
26	3	b	3	III	9
27	5	b	5	III	9
28	1	b	1	I	10
29	4	a	4	II	10
30	2	a	2	III	10
31	1	b	1	II	11
32	6	b	6	II	11
33	8	a	8	III	11
34	4	b	4	II	12
35	1	a	1	II	12
36	7	b	7	III	12
37	1	b	1	III	13
38	8	b	8	III	13
39	7	a	7	III	13

Run	Program Number	Sample	Program	Slot	Tool Used
40	4	a	4	III	14
41	2	b	2	II	14
42	5	a	5	III	14
43	6	a	6	III	15
44	1	a	1	III	15
45	2	b	2	III	15
46	3	a	3	III	16
47	6	b	6	III	16
48	4	b	4	III	16

APPENDIX B

SAMPLE HARDNESS

Sample	Reading 1	Reading 2	Reading 3	Average
1A	48	48	49	48.33
1B	51	48	50	49.67
2A	46	48	48	47.33
2B	47	47	47	47.00
3A	46	48	47	47.00
3B	49	47	50	48.67
4A	48	50	48	48.67
4B	49	52	50	50.33
5A	38	40	39	39.00
5B	42	40	42	41.33
6A	41	40	41	40.67
6B	40	41	40	40.33
7A	40	38	39	39.00
7B	41	42	42	41.67
8A	41	42	42	41.67
8B	39	41	40	40.00

APPENDIX C

SLOT HARDNESS

Slot	Reading 1	Reading 2	Reading 3	Average
1aI	50.00	52.00	49.00	50.33
1aII	53.00	54.00	54.00	53.67
1aIII	52.00	50.00	51.00	51.00
1bI	53.00	53.00	54.00	53.33
1bII	54.00	53.00	54.00	53.67
1bIII	54.00	54.00	53.00	53.67
2aI	52.00	54.00	54.00	53.33
2aII	54.00	54.00	55.00	54.33
2aIII	53.00	53.00	53.00	53.00
2bI	52.00	54.00	53.00	53.00
2bII	49.00	53.00	51.00	51.00
2bIII	52.00	52.00	54.00	52.67
3aI	54.00	54.00	55.00	54.33
3aII	54.00	53.00	52.00	53.00
3aIII	54.00	53.00	54.00	53.67
3bI	54.00	55.00	54.00	54.33
3bII	54.00	52.00	53.00	53.00
3bIII	50.00	52.00	53.00	51.67
4aI	54.00	54.00	55.00	54.33
4aII	54.00	50.00	52.00	52.00
4aIII	55.00	52.00	53.00	53.33
4bI	50.00	48.00	52.00	50.00
4bII	53.00	53.00	52.00	52.67
4bIII	53.00	54.00	54.00	53.67
5aI	48.00	51.00	49.00	49.33
5aII	49.00	49.00	47.00	48.33
5aIII	47.00	48.00	49.00	48.00
5bI	51.00	51.00	50.00	50.67
5bII	50.00	47.00	48.00	48.33
5bIII	49.00	49.00	50.00	49.33
6aI	49.00	52.00	51.00	50.67
6aII	46.00	46.00	48.00	46.67
6aIII	50.00	49.00	50.00	49.67
6bI	50.00	51.00	50.00	50.33
6bII	48.00	47.00	47.00	47.33
6bIII	50.00	51.00	52.00	51.00
7aI	46.00	48.00	48.00	47.33
7aII	49.00	48.00	49.00	48.67
7aIII	49.00	49.00	48.00	48.67

Slot	Reading 1	Reading 2	Reading 3	Average
7bI	48.00	50.00	47.00	48.33
7bII	47.00	49.00	48.00	48.00
7bIII	49.00	50.00	52.00	50.33
8aI	50.00	50.00	51.00	50.33
8aII	48.00	49.00	49.00	48.67
8aIII	48.00	50.00	49.00	49.00
8bI	47.00	47.00	47.00	47.00
8bII	48.00	48.00	48.00	48.00
8bIII	46.00	49.00	48.00	47.67

APPENDIX D

FACTORIAL FIT: SLOT AVERAGE VERSUS A, B, C

Estimated Effects and Coefficients for Slot Average (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		50.8403	0.1865	272.57	0.000
A	4.0139	2.0069	0.1865	10.76	0.000
B	-0.1528	-0.0764	0.1865	-0.41	0.684
C	0.3750	0.1875	0.1865	1.01	0.321
A*B	-0.0417	-0.0208	0.1865	-0.11	0.912
A*C	-0.2361	-0.1181	0.1865	-0.63	0.530
B*C	-0.2917	-0.1458	0.1865	-0.78	0.439
A*B*C	-0.1250	-0.0625	0.1865	-0.34	0.739

S = 1.29225 PRESS = 96.1867
R-Sq = 74.70% R-Sq(pred) = 63.57% R-Sq(adj) = 70.27%

Analysis of Variance for Slot Average (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	195.3	195.3	65.1	38.98	0.00
2-Way Interactions	3	1.711	1.711	0.57	0.34	0.795
3-Way Interactions	1	0.187	0.187	0.18	0.11	0.739
Residual Error	40	66.796	66.796	1.67		
Pure Error	40	66.796	66.796	1.67		
Total	47	263.998				

Unusual Observations for Slot Average

Obs	Std Order	Slot Average	Fit	SE Fit	Residual	St Resid
12	28	50.0000	52.67	0.5276	-2.6667	-2.26R
23	14	46.6667	49.28	0.5276	-2.6111	-2.21R

R denotes an observation with a large standardized residual.

Alias Structure
I
A
B
C
A*B
A*C
B*C
A*B*C

APPENDIX E

ONE SAMPLE T TESTS

One-Sample T: Treatment 1
Test of mu = 49 vs not = 49

Variable	N	Mean	StDev	SE Mean	99% CI	T	P
Treatment 1	18	52.611	1.614	0.380	(51.509, 53.714)	9.49	0.000

One-Sample T: Treatment 2
Test of mu = 47.17 vs not = 47.17

Variable	N	Mean	StDev	SE Mean	99% CI	T	P
Treatment 2	18	52.889	1.410	0.332	(51.926, 53.852)	17.21	0.000

One-Sample T: Treatment 3
Test of mu = 47.83 vs not = 47.83

Variable	N	Mean	StDev	SE Mean	99% CI	T	P
Treatment 3	18	53.333	1.237	0.291	(52.489, 54.178)	18.88	0.000

One-Sample T: Treatment 4
Test of mu = 49.5 vs not = 49.5

Variable	N	Mean	StDev	SE Mean	99% CI	T	P
Treatment 4	18	52.667	1.847	0.435	(51.405, 53.928)	7.27	0.000

One-Sample T: Treatment 5
Test of mu = 40.17 vs not = 40.17

Variable	N	Mean	StDev	SE Mean	99% CI	T	P
Treatment 5	18	49.000	1.328	0.313	(48.093, 49.907)	28.20	0.000

One-Sample T: Treatment 6
Test of mu = 40.5 vs not = 40.5

Variable	N	Mean	StDev	SE Mean	99% CI	T	P
Treatment 6	18	49.278	1.904	0.449	(47.977, 50.578)	19.56	0.000

One-Sample T: Treatment 7
Test of mu = 40.33 vs not = 40.33

Variable	N	Mean	StDev	SE Mean	99% CI	T	P
Treatment 7	18	48.556	1.338	0.315	(47.641, 49.470)	26.08	0.000

One-Sample T: Treatment 8
Test of mu = 40.33 vs not = 40.33

Variable	N	Mean	StDev	SE Mean	99% CI	T	P
Treatment 8	18	48.500	1.295	0.305	(47.616, 49.384)	26.77	0.000