Ranking Wear Resistance of Tool Steels for Woodturning

James T. Staley, Adjunct Prof. in the Dept. of Materials Science and Engineering at North Carolina State University, Raleigh

Woodturners have seen tool makers' ads claiming that their tools last 3X to 10X longer than M2, the most widely used tool steel for wood turning. None of these claims are accompanied with data. I am a metallurgical engineer as well as a woodturner, who much prefers turning to sharpening. Consequently, I proposed to Crucible Materials that they sponsor a relevant Senior Project in the Materials Science and Engineering Dept. of N.C. State U. in Raleigh. The objective was to rank the wear resistance of steels used in woodturning relative to M2 and to develop a metallurgical explanation for the results. Emeritus Prof. Hans Conrad agreed to be co-advisor to the team of Matt Rothwell, Marshall Jones, Will Milan, and Steve Starnes.

When we contacted tool manufacturers for the test procedures that they used to support their claims, we received no response. The methods that Crucible Materials and other steel manufacturers perform to rank wear resistance do not involve cutting any wood. Moreover, we found that different steel companies ranked wear resistance of the same steels in different orders. Consequently, we developed our own evaluation procedures. We wanted a test method that would apply the tool to the wood at a constant angle and feed rate to eliminate the influence of the operator. We also wanted to obtain test data that would be quantitative. We chose Ring Master®, a hobbyist tool that is available either as a stand-alone or as an accessory for many lathe models, Fig. 1. Ring Master® cuts with twin 1/16" wide blades that are akin to a narrow scraper, Fig.2. Porta-Nails Inc., the manufacturer donated the use of two units. We used one to prepare test discs. We equipped the other with a computer controlled DC motor that rotated at 6 rpm to drive the 13 threads per inch screw that advanced the blades.

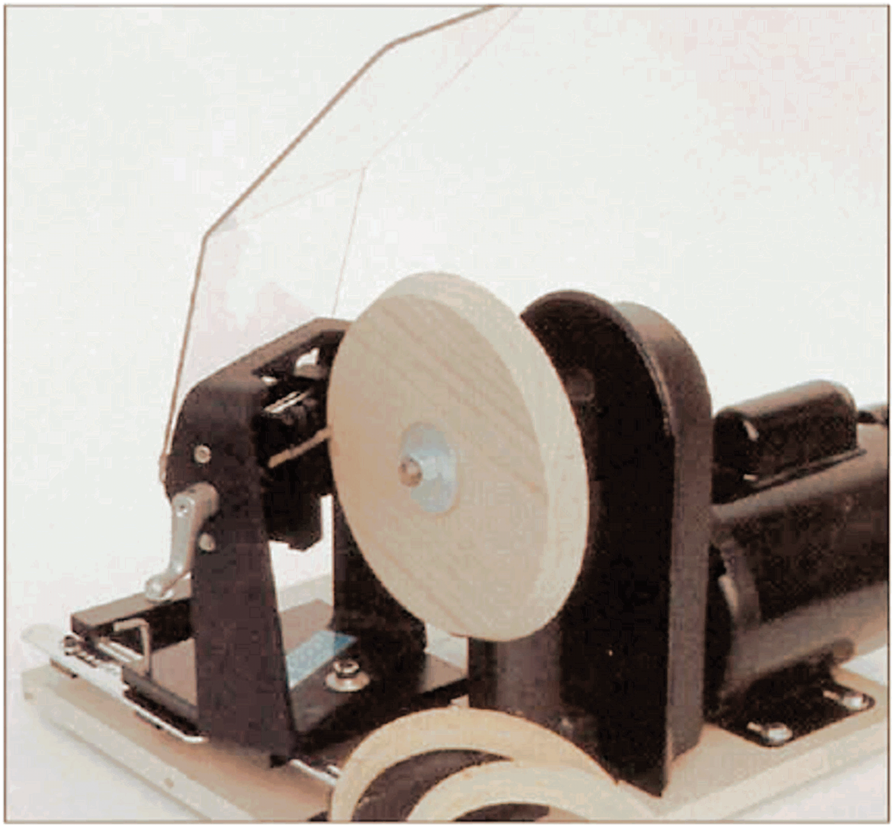

Figure 1. Ring Master® is a hobbyist tool that cuts rings that are glued together to make vessels.

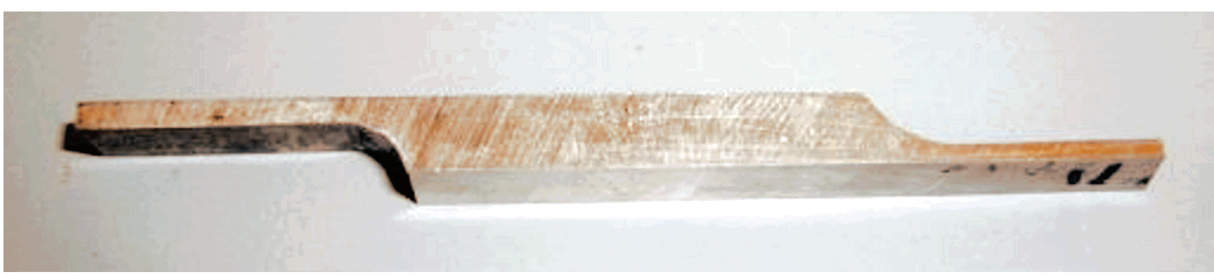

Figure 2. Ring Master® uses two 1/16” x 3/18” blades as cutting tools.

For steels, we used those that steel companies donated, Table 1. T15 is used for Ring Master® blades. 10V is also known as A11 and is used in premium woodturning tools. 15 V has higher vanadium. Crucible Materials recently developed Rex86 for improved wear resistance. All were supplied in the fully heat treated, triple tempered condition. Porta-Nails, Inc. ground the 3/16” square steel rod to sharpened blades ready for test.

In addition, we evaluated effects of cryotreatment on M2 and 10V. Cryotreatment was performed by a commercial heat treatment shop that specializes in cryotreatment below -300 F. They performed the treatment on triple tempered blades.

Steel	C	Mn	Si	Cr	V	W	Mo	Co
M2 [1,3]	0.85	0.3	0.3	4.2	1.9	6.0	5.00	0
T15 [1,4]	1.60	0.3	0.3	4.3	5.0	12.0	0.80	5.0
Rex86 [2,4]	2.0	0	0	4.0	5.0	10.0	5.0	9.0
10V [2,4]	2.45	0.5	0.9	5.3	9.8	0	1.3	0
15V [2,4]	3.4	0.5	0.9	5.3	15.0	0	1.3	0

[1] *donated by Latrobe Steel* [2] *donated by Crucible Materials*
[3] *made by conventional ingot metallurgy* [4] *made by powder metallurgy*

Table 1, Steels used for test program

For wood, we chose both hard, purple heart, and soft, poplar, woods that are used by woodturners. We dropped the poplar early in the investigation because it took so long to wear even the M2.

Test Procedure

To perform a test, the students mounted an 11.5" x diameter disc on the Ring Master(R), Fig. 3. They adjusted the tool carriage so that the blades would enter at 5 1.2" radius and rotated the disc at 800 rpm. The computer program automatically controlled the motor to feed one of the blades into the disc at a rate of about ½" in./min. until it had cut half through the 13/16" thickness. Then it reversed the direction of the motor to withdraw the blade and feed the blade from the other side to complete the through-cut. After the cut, they removed the ring that was separated from the disc and advanced the blade about 3/8". The students repeated the process until they had made 12 cuts, Fig 4 Wood removal rate was about 1 in.^{3}/min. for the 1st cut and about ½ in.^{3}/min. for the 12th cut. For each steel, they cut 3 disks for a total of 36 cuts per steel blade. The operation removed a total volume of over 25 cubic inches. Table 2 presents equivalent volumes of wood removed during spindle and bowl turning.

	Hemispherical Bowl	**4" diameter x 6 " spindle**
1st disc	3" inside diameter	3 ½" diameter
2nd disc	4" inside diameter	3 3/32" diameter
3rd disc	4 1/16" inside diameter	2 5/8" diameter

Table 2 Shows equivalent volume of wood turned from typical shapes

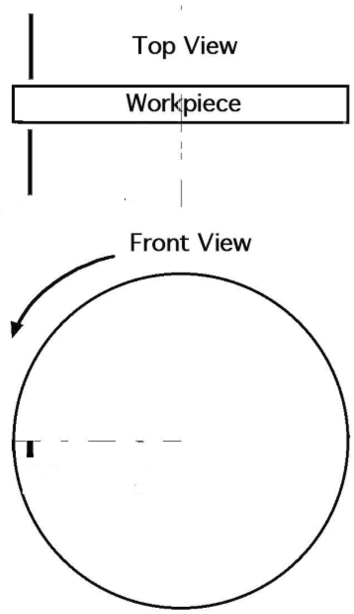

Figure 3. Experimental set-up for 1st cut. Blades were moved manually towards the center after each through-cut.

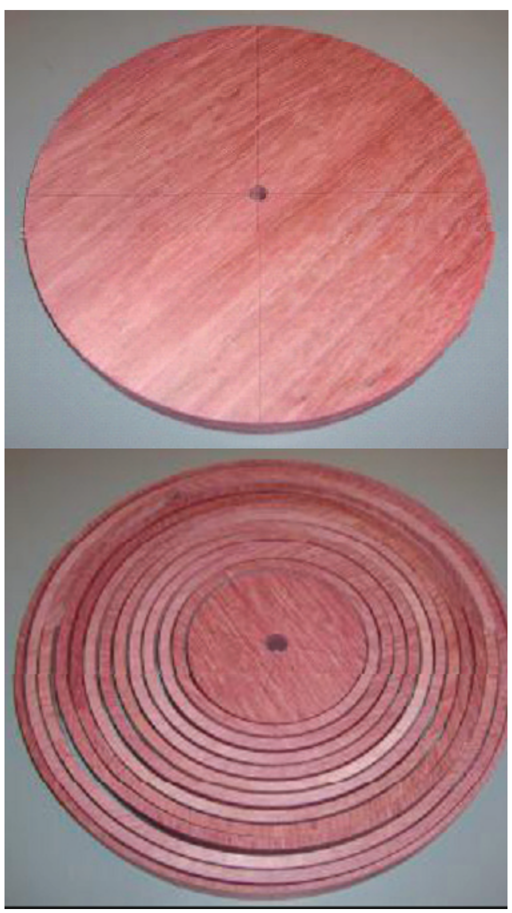

Figure 4. Discs before and after cutting

Evaluation
As a tool wears, more force must be applied to enter the wood at a constant rate because of the increased friction. Current on a constant voltage motor is directly proportional to force. Consequently, the students recorded the current, and we used it as a quantitative measure of tool wear.

Weight loss of a tool is a standard method of measuring wear. Our efforts to do this were frustrated because of a tenacious film of resin that exuded from the purpleheart and coated the blades. Even the most worn blade weighed more after the test than before.

The far corner of each blade wore preferentially because of the test set-up. The students measured the diameter of curvature of the worn corner using a scanning electron microscope. We used the square of either the diameter or the radius as a quantitative measure of wear because those values are proportional to the volume of steel worn away..

Results
We plotted average current per cut (proportional to force) versus volume of wood removed for each steel. Current while cutting with M2 blades began to increase immediately, Fig 5. Current for the other steels took longer before it began to increase, Fig. 6. We decided that the most useful way to interpret the vast quantity of data was to use the average of the current over the entire 72 cuts (12 cuts per side on 3 discs). The steels are arranged in order of increasing wear resistance as indicated by average current in Fig. 7. Effects of cryotreatment were mixed and not extensive. Current of cryotreated M2 was higher than that of untreated M2 while current of cryotreated 10V was lower. This suggests that cryotreatment had no effect.

Figure 5. M2 blades began to wear immediately as indicated by increase in current to keep blade entering the wood at a constant rate. Cryotreated M2 behaved similarly. The students reported that both M2 and cryotreated M2 blades caused the wood to smoke during the final cuts on the 3rd disc.

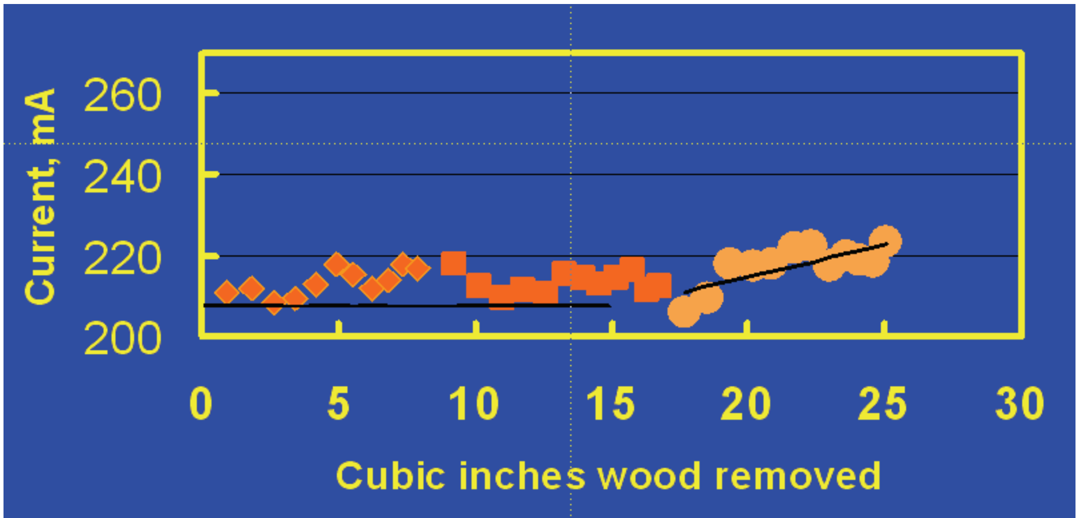

Figure 6. Wear didn't begin appreciably on 15V until the 3rd disk was cut. Rex86 behaved similarly. The other steels performed intermediate to that of M2 and 15V.

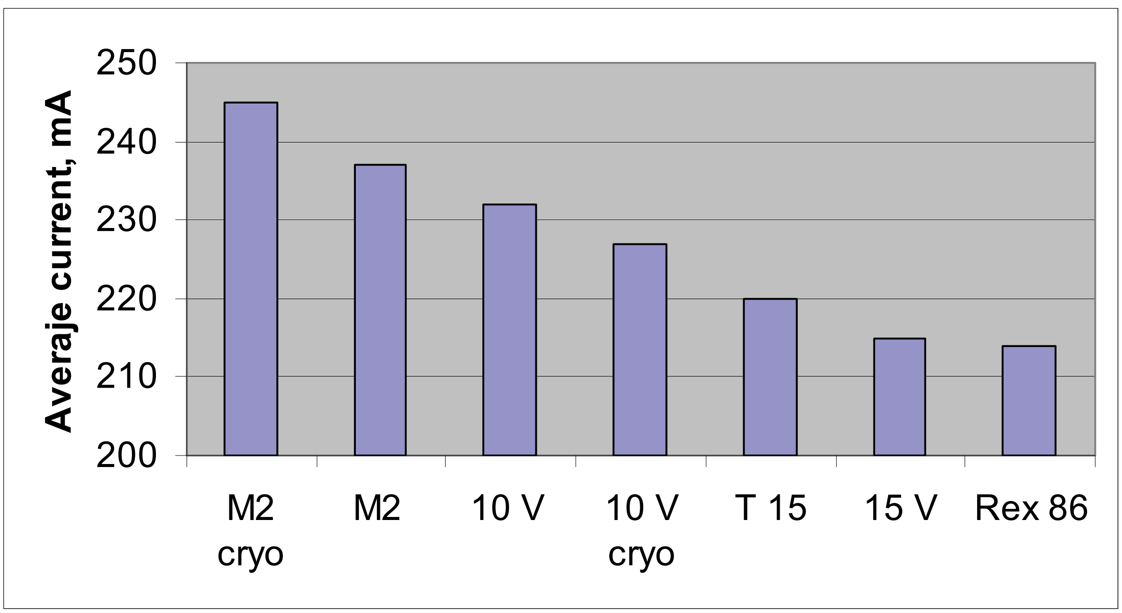

Figure 7. Steels are ranked according to current averaged over the entire 72 cuts. Low current indicates less force required to keep the blade entering the wood at a constant rate and, hence, higher resistance to wear.

The worn corner of one blade of each steel are depicted in Fig. 8. Volume of metal worn away is proportional to the square of either the radius or diameter of curvature of the worn corner, so we used those values to interpret the data. The results are summarized in the bar graph in Fig 9. In this case, the cryotreated versions of M2 and 10V were slightly more worn than their untreated counterparts. This confirms that cryotreatment had no effect on resistance to wear.

Plots of average current vs. the square of the radius of the worn corner showed that average current and corner wear were linearly proportional, Fig. 10.

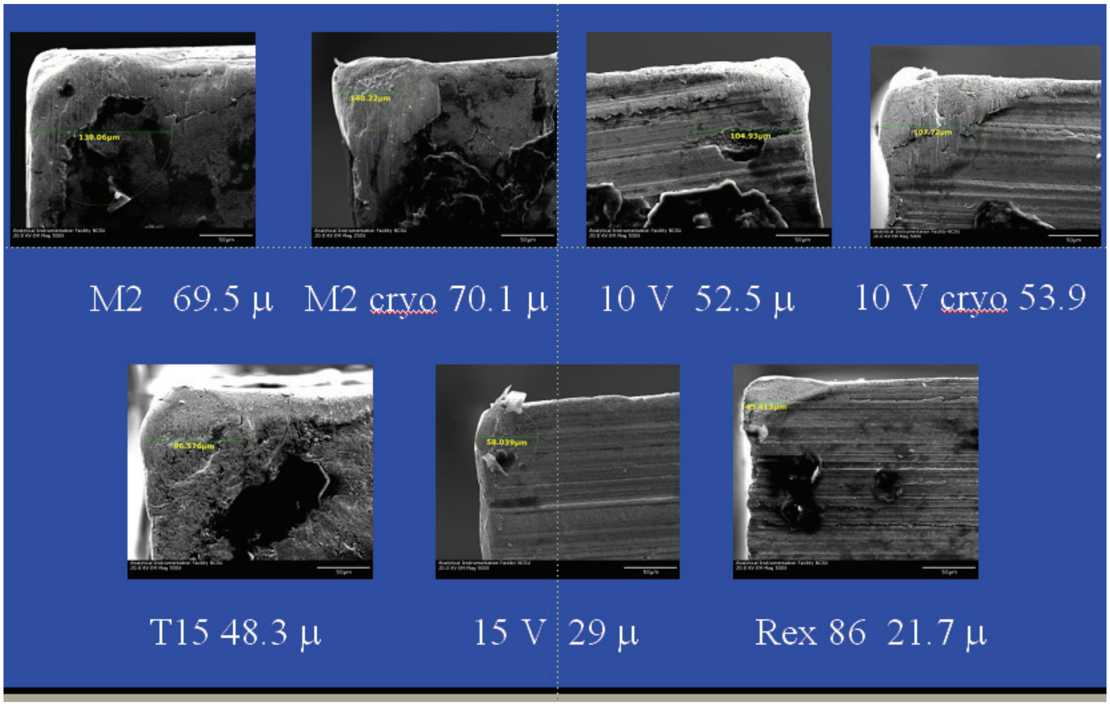

Figure 8. Illustrates worn corner of each steel. Measurements of the radius of curvature of the corner are indicated.

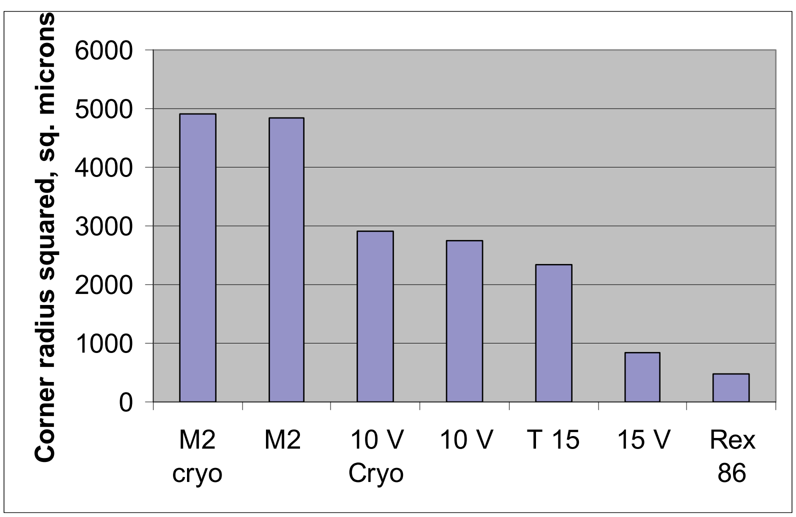

Figure 9. Steels arranged in increasing resistance to corner wear

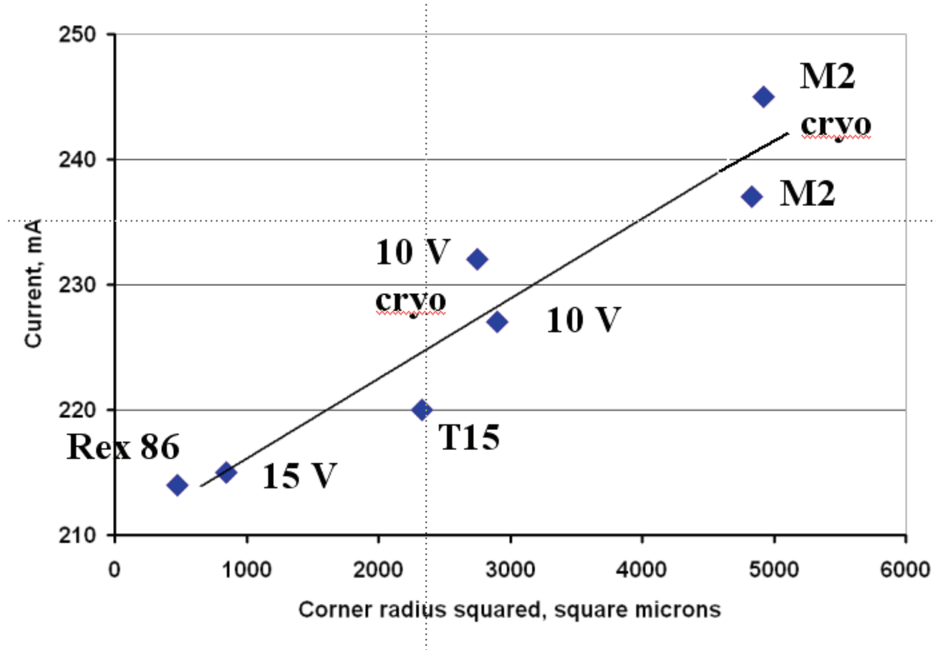

Figure 10. Corner wear as measured by the square of the radius of the worn corner and average force during cutting as measured by average current are linearly related

Metallurgical interpretation of results

The principle metallurgical differences in the steels were volume fraction of carbides and hardness. Consequently, the students measured the Rockwell C hardness and determined the volume fraction of carbides, Figs. 11a and b illustrates the carbides in the steels with the lowest, M2, and highest, 15V, volume fractions of carbides. The figure also illustrates the effects of powder metallurgy processing. The carbides in 15V are finer and more uniform in size.

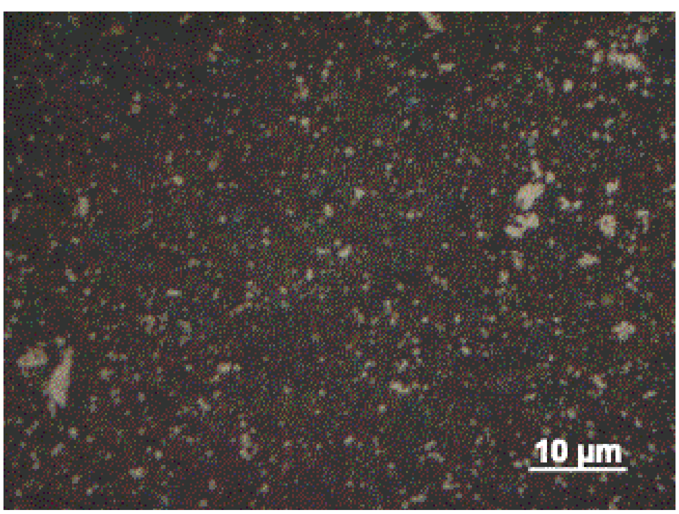

Figure 11a. Volume fraction, fc, of M2 was 0.099. Note the mixture of coarse and fine carbide particles.

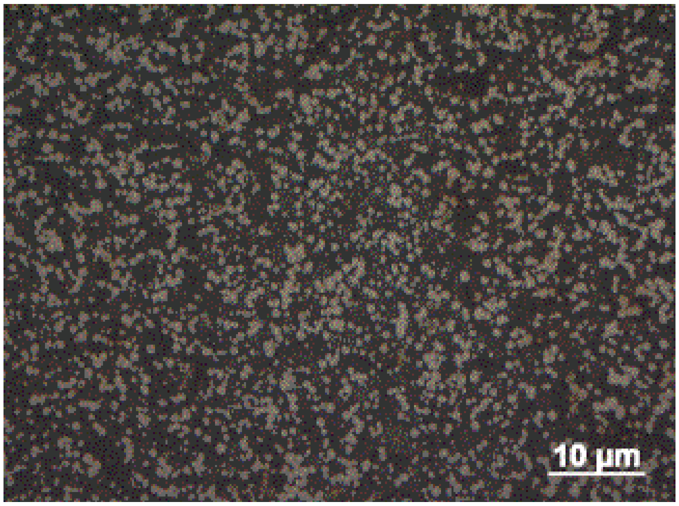

Figure 11b. Volume fraction, fc, was 0.224. Note the finer and more homogeneously distributed carbides compared to M2.

Volume fraction, fc, and hardness of all steels are presented in Table 3 We converted Rockwell C hardness to Vickers hardness, Hv because Hv is a more fundamental property.

Steek	Volume fraction carbides, fc	Rockwell hardness, C scale	Vickers hardness, Hv, Kg/mm^2
M2	0.099	64.0	800
T15	0.185	64.9	829
Rex86	0.172	67.5	920
10V	0.135	60.5	709
15V	0.224	60.9	718
M2 cryo	0.099	63.3	780
10V cryo	0.135	60.6	711

Table 4. Metallurgical parameters

Professor Conrad developed a theory of wear that predicts that resistance to wear will increase as the product of Vickers hardness, Hv, and the ratio of the volume fraction of carbides to the volume fraction of the steel matrix, fc/(1-fc), increases. The plot of the square of the corner diameter, D^2 vs. Hv * fc/(1-fc) in Fig. 12 shows that this measure of wear decreased linearly as this product increased. Similarly, average current during turning the 3 discs, I, decreased linearly with increasing values of Hv * fc/(1-fc), Fig. 13. Normalizing the results by dividing all data by the data for M2 provides the relative merit of each steel, Fig. 14. The bar graph in Fig. 15 illustrates the ranking.

Because cryotreatment has no effect on carbides and negligible effect of hardness of triple tempered steel, performance is predicted to be the same as that of untreated material. The lack of effect of cryotreatment is not surprising when one considers the metallurgical changes during heat treatment described in the Appendix.

The relatively low advantage of the highly touted 10V steel was unexpected. It contains a large amount of vanadium which forms vanadium carbides, the hardest carbides in tool steels. Despite this difference, our wear equation is insensitive to the type of carbide. We believe that the reason for the insensitivity to carbide type is because all carbides are so much harder than even the hardest wood that it doesn't matter for woodturning.

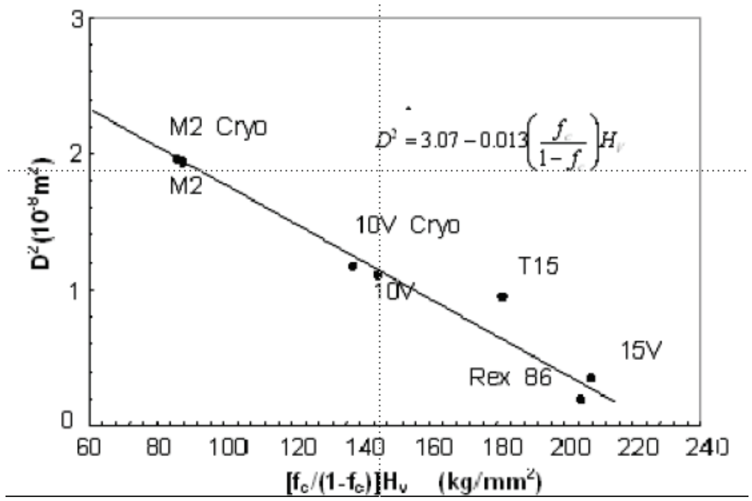

Figure 12. Resistance to corner wear, as measured by the square of the diameter of curvature if the worn corner, increased linearly as the product of Vickers hardness, and the ratio of the volume fraction of carbides to the volume fraction of steel matrix increased.

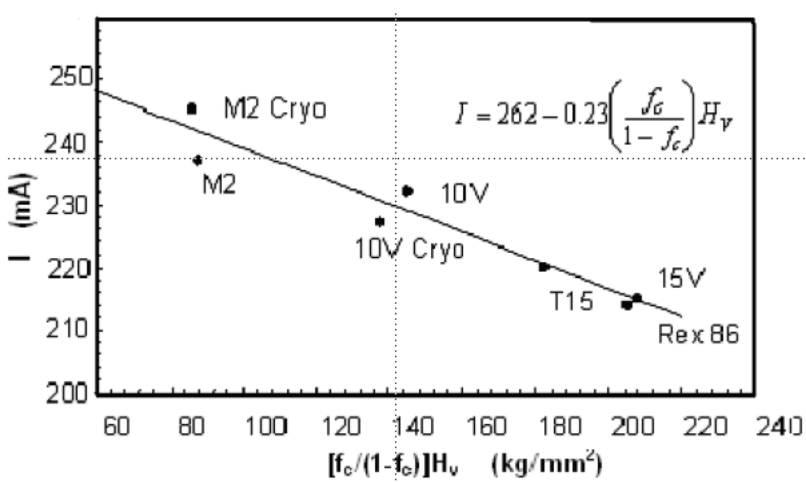

Figure 13. Resistance to wear, as measured by the average current, also increased linearly as the product of Vickers hardness and the ratio of the volume fraction of carbides to the volume fraction of steel matrix increased.

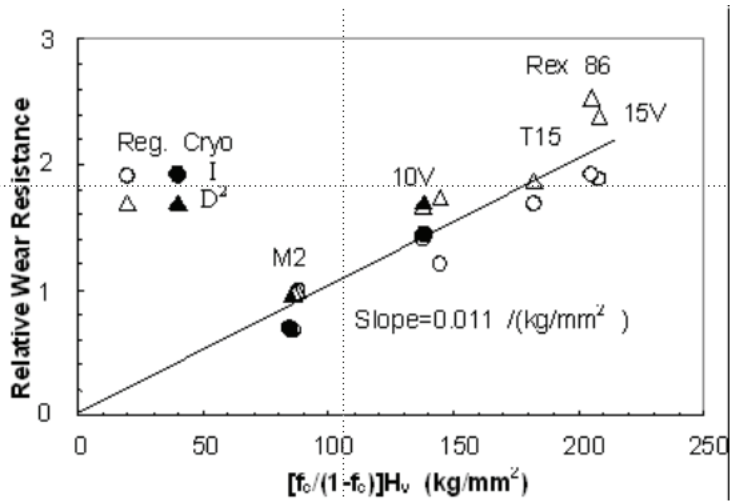

Figure 14. Normalizing the data with respect to M2 provides a way to rank the steels relative to that baseline material.

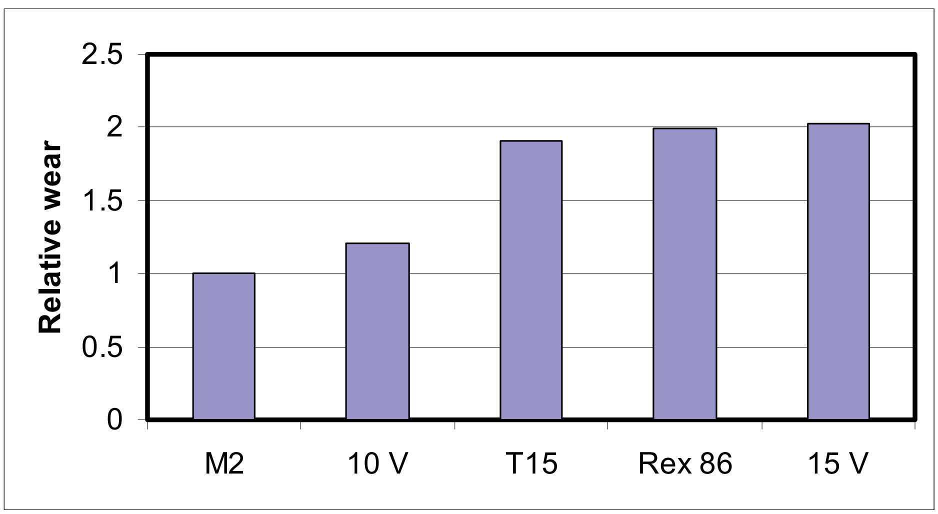

Figure 15. Wear resistance of tested tool steels relative to M2 based on Hv * fc/(1-fc).

Predicting performance of other tool steels

Armed with the knowledge of the linearly relationship between the resistance to wear and Hv * fc/(1-fc), we can predict the relative performance of other tool steels if we know their hardness and volume fraction of carbides. We contacted several tool manufacturers who directed us to their steel suppliers for the data. The results are summarized in the bar graph in Fig. 16. All are predicted to out perform M2. None attained the amount of advantage presented in the tool makers literature.

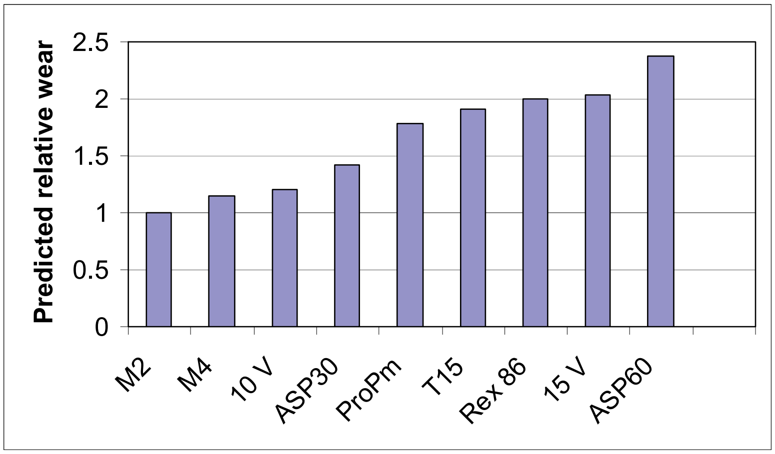

Figure 16. Predicted relative wear resistance of tool steels when turning hard, dry wood

Conclusions

Relative wear resistance of tool steels when turning hard, dry wood rank similarly using either measurements of corner wear or average current of a motor driving the tool into the wood at a constant rate.

These measures of resistance to wear increase linearly as the product of Vickers hardness and the ratio of the volume fraction of carbides to volume fraction of the steel matrix increases.

Using this criterion, wear resistance of any tool steel can be calculated if these values are known.

All of the steels advertised as being more wear resistant than M2 are truly more resistant. However, the relative wear resistance is less than claimed.

Cryotreatment applied to triple tempered tool steel has no effect on wear resistance.

Appendix

Simplified description of heat treatment of tool steels.

Before heat treatment, the structure is a soft matrix of essentially pure iron and alternating platelets of carbide and pure iron called pearlite. The initial high temperature treatment dissolves the carbide platelets. The matrix structure formed at the high temperature contains carbon and alloying elements. And is referred to as Austenite. The carbon and alloying elements that didn't dissolve at the initial high temperature is in the form of carbides consisting mainly of W, Mo, and V. These are the carbides that are in the term fc. When this structure is quenched, most of the austenite transforms to a hard brittle Martensitic structure which traps the carbon. To make the material useful, it must be tempered at an intermediate temperature. This produces the structure known as tempered Martensite. When highly alloyed steels such as tool steels are quenched not all of the Austenite transforms to Martensite. Cooling to temperatures near -300 F, transforms the retained Austenite to Martensite. Tool steels, however, are triple tempered. One of the effects of triple tempering is to transform the retained Austenite to Martensite. Consequently, we anticipate that cryotreatments of tool steels, regardless of when the treatment is applied will have the same structure and properties of triple tempered tool steels.