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# Determining the Machinability of High Performance Steels

## Final Report

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*Prepared By:*

Machining Research, Inc.
7785 Foundation Dr. Suite One
Florence, KY 41042

*Edited and Contributed To By:*

Illinois Department of Transportation
Bureau of Materials & Physical Research
126 E. Ash St.
Springfield, IL 62704

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16. Abstract
Two high performance (HP) steels, ASTM A709 HPS 70W and ASTM A710 Grade B, were compared with ASTM A36, a plain carbon structural steel widely used in construction for plates, shapes, flats and sheet products. In general, the HP steels had equivalent or slightly better machining characteristics than the A36 structural steel.

When cut by oxyacetylene, A36 steel had a wider and more diffuse heat-affected zone (HAZ) than did the HP steels. Plasma cutting showed a much narrower HAZ for all three steels, with A36 having the highest surface hardness at 420 Vickers. When each steel was cut by band saw blades, use of M42 high speed steel bimetal blades at 120 feet per minute (fpm) using heavy duty mineral oil as a cutting fluid provided the longest saw blade life.

For face milling, surface finishes were excellent for the HP steels, providing surface roughness comparable to those obtained by grinding. Typical face milled surfaces for the HP grades were 15 micro-inches (µin) and 20 µin for A36 steel. For end milling, the best tool life and the lowest surface roughness was obtained by use of titanium nitride-coated high speed steel, with a feed rate of 0.004 inches per tooth and a cutting speed of 100 fpm for ¾ inch diameter cutters. Grinding produced very smooth surfaces, 4-9 µin parallel to lay and 8-22 µin perpendicular to lay.

For hole drilling, annular cutting drills provided accurate diameter holes at significantly less power draw than with conventional twist drills, particularly when using titanium nitride-coated high speed steel drills. Twist drills had slightly better performance drilling HP steels when compared to plain carbon steel A36. This was attributed to the uniformity of HP steel ferrite matrix and fine grain size, compared to A36 steel which had a larger grain size, higher carbon content, and a softer ferrite matrix. For ¾ inch high speed steel twist drills at 75 fpm, about 40% more holes were drilled in the HP steels than in the softer A36 steel.

Based on this work, the machinability rating of the A36 steel is 45-50% and the machinability of the HP steels is about 50-60%, both compared to the reference point free-machining steel SAE 1212 at 100%.

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## DISCLAIMERS

Throughout this report, several companies, trade names and products are mentioned to describe the various machining processes. Use of these names or products does not constitute an endorsement of these companies or their products by the authors, the FHWA, nor any of the pooled fund states that support this project. The companies, trade names and products are only mentioned as indicative of typical practice, and there may be many other suitable enterprises or equal products that may be substituted. The citations of specific trade names or products are for illustrative or comparison purposes only, and are strictly intended to show the effects of commodity products and services on machining processes in general.

## ABBREVIATIONS, SYMBOLS AND ACRONYMS USED IN THIS REPORT

AD = axial depth or distance

ASTM = American Society for Testing & Materials

A36 = ASTM A36 carbon structural steel

A709 = ASTM A709 Grade HPS 70W alloy structural steel for bridges

A710 = ASTM A710 Grade B alloy structural steel

BHN = Brinell Hardness Number

BUE = built-up edge

CNC = computer numerical control

$cm^3$ = cubic centimeters

Cobalt = a higher performance tool steel containing both molybdenum and cobalt

DOC = depth of cut

fpm; FPM = feet per minute

HAZ = heat affected zone

hp = horsepower

HP = high performance

HSS = high speed steel

ID = inside diameter

" = inch (used in graphs of this report)

in = inch

$in^2$ = square inches

$in^3$ = cubic inches

ipm; IPM = inches per minute

ipt; IPT = inches per tooth

IN/REV = inches per revolution

μin = micro-inches

μm = micrometer

min = minute; minimum (depends on sentence context)

ksi $[in]^{1/2}$ = fracture toughness of steel & other metals, in inch-pound units

M1 to M48 = series of tool steels containing molybdenum

NDA = no data available

OD = outside diameter

RA; $R_a$ = average surface roughness, in microinches

RD = radial depth or distance

RDOC = radial depth of cut

rpm = revolutions per minute

SAE 1212 = a free-machining steel with high sulfur and phosphorus content

1020 = SAE 1020 steel, a commonly used plain carbon steel

TiN = titanium nitride

TRIM SOL = brand name of a commonly used cutting fluid

## CONVERSIONS OF US CUSTOMARY TO INTERNATIONAL (SI) UNITS

Throughout this investigation, US Customary Units were used as quantities for tool parameters and outputs of measuring instruments. The following are conversions of US Customary Units to International (SI) Units for the various quantities cited in this report.

$^oC = [^oF - 32] / 1.8$

$^oF = [1.8 \times {}^oC] + 32$

1 inch = 2.54 centimeters (cm) = 25.4 millimeters (mm)

1 square inch ($in^2$) = 6.45 square centimeters ($cm^2$)

1 cubic in ($in^3$) = 16.39 cubic centimeters ($cm^3$)

1 inch per tooth (ipt) = 25.4 mm per tooth

1 foot per minute (fpm) = 5.08 millimeters per second (mm/s)

1 foot-pound (ft-lb) = 1.356 joules (J)

1 micro-inch (μin) = 0.0254 micrometers (μm)

# EXECUTIVE SUMMARY

This report compares the machinability of conventional ASTM A36 structural steel plate with ASTM A709 HPS 70W and ASTM A710 Grade B high performance (HP) structural steel plates. These steels were evaluated by the machining processes of sawing, cutting, milling, grinding and drilling. Based on the tests conducted in this investigation, the machinability of A709 HPS 70W and A710 Grade B was equivalent or better than A36 steel. Evaluations included plasma and oxyacetylene cutting, measuring the surface roughness of each steel after machining, the tool wear of the cutters and twist drills used, the amount of metal removed by saw blades, grinding wheels, face and end mill cutters, and the number of holes drilled with annular (hollow) and twist drill bits.

When cut by oxyacetylene, each steel had cut surfaces that were comparable and had similar surface roughness. However, the heat affected zone for A36 was wider and deeper for A36 compared to A709 and A710 due to the higher carbon content of A36. In contrast, when cut by plasma, the heat affected zones were similarly shallow for all three steels, and the surface roughness of the cuts were approximately equivalent. Using M42 high speed steel saw blades and comparing each steel based on a uniform blade wear of 0.020 inches, 23% to 58% more material was cut from A709 and A710 than from A36.

When the three steels were ground using aluminum oxide wheels, the surface roughness for each steel was determined to be comparable. The average surface roughness for all three steels when ground parallel to lay (rolling direction) was about 4-6 microinches (µin). The A709 HPS 70W had a slightly higher surface roughness than A36 or A710 when ground perpendicular to lay.

When the three steels were drilled with M2 high speed steel annular drill bits, the number of holes drilled was very comparable. The number of holes nearly doubled, except for the A709 HPS 70W steel, when the M2 cutting tips were coated with titanium nitride. The inside roughness of the drilled holes were very similar. More holes were drilled in A709 and A710 steel than in A36 when compared by equivalent tool wear. More holes were drilled with ¾ inch high speed steel twist drills in A709 and A710 than in A36, particularly at lower cutting speeds.

Results for face milling were very positive. The surface roughness for both A709 and A710 was 15 µin and was 20 µin for A36. The surface roughness values obtained by face milling A709 and A710 steels were almost equivalent to those of ground surfaces.

Extensive tests were conducted with end mills. Use of a ½ inch diameter M2 high speed steel end mill resulted in a 160 µin surface roughness for A36, but was 60-70% better for the HP steels. When the end mill diameter was increased to ¾ inch using M2 high speed steel, surface roughness values were virtually equal at about 45-50 µin for the three steels.

M2, M42 and titanium nitride coated end mills had similar tool life for the HP steels, but A36 had sustained about 40-56% more wear than its counterparts. Cutting times and the amount of metal removed from A36 plates was about 25-40% less than A709 HPS 70W and about 30-46% less than A710 Grade B.

HP steels have higher strength and impact toughness than A36. Since higher strength and toughness typically decrease machinability, the machinability of the HP steels was in question. Somewhat unexpectedly, the surface roughness A36 carbon steel was found to be slightly higher than the HP steels. In several cases, the machinability of HP steels was better than A36. The A36 plate had a larger grain size, numerous hard iron carbide pearlite islands and prominent banding in a soft ferrite matrix. In contrast, the HP steels have lower carbon contents, finer grain size and a harder ferrite matrix due to their higher alloy content and a very fine dispersion of hardened intermetallic precipitates in A710 Grade B. This uniformity provided a smoother surface when milled or ground and better chip formation.

ASTM A588 and A572 structural plate steels were not evaluated in this study due to cost constraints. However, it is anticipated that these steels would have machinability values quite similar to HP steels if they have fine grain sizes, minimal banding of pearlite and carbon contents of 0.15% or less. Turning and tapping were not part of this investigation; however, based on this work, the machinability of A710 Grade B and A709 HPS 70W steels was estimated to be about 50-60% of SAE 1212 steel at 100% when turned or tapped.

The machinability values of common carbon and alloy steels widely used in the construction of structures, machinery, bridges and highways, based on data obtained from authoritative sources, was also summarized in this report. Typical applications for these steels and their range of machinability, primarily obtained from the turning of bars, were compared to the machinability of free-machining SAE 1212 steel bars.

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# DETERMINING THE MACHINABILITY OF HIGH PERFORMANCE STEELS

## 1. GENERAL BACKGROUND

A new class of structural steels has been recently introduced for use in bridges and related transportation structures as a replacement to ASTM A36 plain carbon steel which is the structural equivalent to SAE 1022. ASTM A36 has been used in thousands of bridges since its introduction in the late 1950s. There has been a gradual movement since that time by bridge designers to increase the minimum design yield strength from 36 ksi to 50-70 ksi, depending on dead and live load stresses and span requirements of the bridge. These newer high performance (HP) steels augment ASTM A572 and A588 50 ksi yield strength structural steels commonly specified by many bridge designers today.

### *A. Composition and Properties of the Steels*

Compositions for ASTM A36, and the two HP steels tested in this study are defined in ASTM Standards A709 and A710. The composition and mechanical property ranges for these steels can be found in *Text Tables 1a and 1b.* A709 HPS 70W and A710 Grade B HP steels have minimum yield strengths of 70 ksi and ductilities of 19% elongation. An A709 HPS 50W 50 ksi yield strength has already been standardized, and a 50 ksi A710 Grade C is awaiting ASTM and AASHTO approval. Only the 70 ksi versions of A709 and A710 were tested in this investigation.

The principal differences between these steels vs. those of conventional structural steels are their remarkably high impact notch toughness and lower carbon contents. Typical structural steels used in fracture-critical applications require only 25 ft-lbs at 40°F, whereas HP steels require 35 ft-lbs at –10°F per ASTM A709. ASTM A710 requires even higher notch toughness values of 20 ft-lbs at –50ºF. It is not unusual for these steels to exhibit a notch toughness of 100 ft-lbs or more at –40°F.

### *B. Machinability*

Various components and elements used in bridges and structures are often machined to permit fit-up and assembly during fabrication or final construction. For fixed bridges, holes must be drilled; bars may be turned and threaded for anchors bolts or bolting; structural plates, shapes, stiffeners and bearing blocks are cut, milled and ground. Plates are sometimes punched and occasionally tapped for threading. For movable bridges, their associated machinery, gears, shafts, bearings, racks and framing members are routinely machined to ±0.001 inch tolerances, with surface roughness values ranging from as low as 8 µin for journal shafting and up to 250 µin for bearing bases.

The machinability of materials is related to their microstructure, geometry and the tools required to cut and shape them. There is no universal definition of machinability. A widely used general definition of a machinable material is when the greatest amount of it can be removed in the shortest time for a given tool, with a satisfactory or specified finish, at minimum overall cost (Ref K). Other authorities consider the factors of tool life, tool forces, energy consumption and the quality of the surface finish to determine machinability of a material (Ref H).

Tool life, as measured by the time of operation up to the point when the tool must be reground for sharpness or replaced outright, has been the most commercially used measure of machinability. Tool life is often determined by a particular tool cutting a specific material obtained by plotting tool speed vs. tool life on log-log coordinates to determine the following expression:

$$V \times T^n = C$$

Where

V = cutting speed, fpm
T = time, minutes
n = slope of the log-log plot
C = 1 minute intercept

Cutting speeds are usually inversely proportional to material hardness, but are directly related to material conductivity. Conductive materials are able to dissipate much of the heat generated by the cutting tools. Highly conductive and generally softer aluminum and copper alloys have greater machinability than steel or titanium alloys due to their lower conductivity.

Surface finish is also an important variable, since it is typically specified and often determines operability, fit-up and fatigue life of a stressed component.

Another measure of the machinability of a material depends on how much volume can be removed at certain spindle speeds and depths of cut. The diameter of a bar, or the amount of surface area cut on a plate, will determine the cutting speed or feed rate. An additional determination of machinability is the specific horsepower (hp) or kilowatts (kW) required to remove 1 cubic inch ($in^3$) or 1 cubic centimeter ($cm^3$) of metal. For example, the specific hp to machine 1 $in^3$ of 2024 aluminum alloy is 0.43; for 360 free-cutting brass, 0.41; 0.59 for SAE free-machining steel, and approximately 0.67 for ASTM A36 structural steel. When these values are compared with various materials, machinability ratings can be developed for different machining processes. Machinability ratings for materials are widely used by various industries. Many years ago, SAE alloy 1212 free-machining steel with high sulfur and phosphorus contents, was chosen for convenience as a baseline. SAE 1212 was assigned an arbitrary machinability rating of 100%. Other free-machining steels were subsequently developed, such as AISI 12L14, which can have machinability ratings of up to 250% of SAE 1212. In comparison, ASTM A36, a very common structural steel used in many existing and some new structures, has a machinability rating that varies from 40-50% of SAE 1212. ASTM A36 has a typical range of 0.16%-0.25% carbon content with substantial manganese variance, where most steel producers keep sulfur and phosphorus in A36 to low levels to improve toughness and weldability.

*Text Table 1a* / COMPOSITION of ASTM A36, A709 HPS 70W and A710 GRADE B STEELS

| Element | A36 | A709 HPS 70W | A710 Grade B |
|---|---|---|---|
| Carbon** | 0.26 max | 0.11 max | 0.03-0.09 |
| Manganese*** | 0.80-1.20 | 1.10-1.35 | 0.45-1.30 |
| Phosphorus, % max | 0.04 | 0.020 | 0.025 |
| Sulfur, % max | 0.05 | 0.006 | 0.025 |
| Silicon | 0.40 max | 0.30-0.50 | 0.30-0.50 |
| Copper, % min when specified | 0.20 | 0.25-0.40 | 1.25-1.50 |
| Nickel | ... | 0.25-0.40 | 0.80-1.00 |
| Chromium | ... | 0.45-0.70 | 0.30 max |
| Molybdenum | ... | 0.02-0.08 | 0.25 max |
| Vanadium | ... | 0.04-0.08 | ... |
| Columbium | ... | ... | 0.02-0.06 |
| Aluminum | ... | 0.010-0.040 | ... |
| Titanium | ... | ... | 0.01-0.03 |
| Nitrogen | ... | 0.015 max | ... |

(...) Ellipses indicate that there is no requirement established for this element by ASTM.
** For A36, carbon is 0.25 to 0.27% max, depending on thickness; 0.26-0.28% max for bars, depending on thickness.
***For A36, manganese is not restricted for shapes and bars ¾ inch [20 mm] or less; 0.60-0.90% for bars over ¾ inch thick.

*Text Table 1b* / MECHANICAL PROPERTIES of
ASTM A36, A709 HPS 70W and A710 GRADE B STEELS

| Element | A36 | A709 HPS 70W | A710 Grade B |
|---|---|---|---|
| Yield strength, ksi | 36 min | 70 min | 70 min |
| Tensile strength, ksi | 58 - 80 | 85 - 110 | 80 min |
| % Elongation, 2 inch gage | 23 | 19 | 20 |
| V-Notch impact toughness, ft-lbs | 15*<br>*zone dependent | 35 at -10°F | 35 @ -10°F (Class 3)<br>20 @ -50°F (Class 2) |

The general microstructures of plain carbon steel vs. HP steel are shown in *Figures 1 and 2.* The grain size of A36 is considerably larger than the fine-grained A710 Grade B, and has large prominent bands of hard pearlite in between the softer ferrite. In contrast, the microstructure for A710 Grade B HP steel is very fine grained, and the ferrite matrix is hardened by alloying elements and fine copper-nickel-iron precipitates that are uniformly dispersed throughout the matrix.

The machinability of free-machining steels is 100% or more because of the presence of high levels of interstitial alloying elements or brittle phases, which aid in the cutting process by forming small, short chips. The dispersal addition of lead, bismuth or tellurium permits tool sliding, rather than galling of the metal onto the cutting tools. When carbon content is low, there are fewer hard phases which can cause nicking or chipping of the tool. However, although free-machining steels have better facility for chip formation during machining, they have substantially lesser ductility and low impact energy absorption when measured by the Charpy V-notch impact toughness test. They have a limited tolerance for cracking and rupture under high loads and stresses. On the other hand, high performance (HP) steels have great toughness. They have lower carbon contents, typically ranging from 0.05%-0.11% carbon, which is about half the carbon content of A36. In addition, their phosphorus and sulfur contents are very low, at times less than 0.01%. However, if phosphorus and sulfur contents were increased in HP steels to levels found in free-machining steels to improve their machinability, such increases would come at a sacrifice of toughness.

## 2. PURPOSE OF THE RESEARCH

This research was pursued to determine if the toughness of HP steels would result in a greater amount of energy for break-off of cut metal, and if their high ductility would lead to longer or stringy chip formation. Stringy chips can cause excessive heat, galling of the machined surface, hazards to the operators, plus significant wear and metal accumulation on cutting tools. The purpose of this research was to define the machinability of high performance steels in quantifiable terms, such as tool life, tool wear, ability to remove metal and surface roughness. This research included two HP steels, thermo-mechanically processed ASTM A709 HPS 70W and hot rolled ASTM A710 Grade B. Because the machining characteristics of steels, which vary with microstructure, hardness, chemical composition, ductility and conductivity, this investigation was undertaken to compare the HP steels with ASTM A36, one of the principal standard structural steels that has been used for bridge construction in the United States for more than 50 years. ASTM A36 has a microstructure of low carbon ferrite interspersed with pearlite colonies of iron carbide (cementite), compared to the harder ferritic microstructures of A709 and A710 HP steels that have minimal iron carbide dispersal present due to their low carbon contents.

The research was intended to provide fabricators with useful machining process parameters when cutting, sawing, milling, turning and drilling high performance and other steels used in bridges and transportation structures.

*Figure 1.* The microstructure of ASTM A36 is characterized by large grains of ferrite, and numerous large bands pearlite oriented in the longitudinal rolling direction. Since the ferrite is largely free of carbon which is segregated primarily in the iron carbide of the pearlite, the ferrite grains are quite soft compared to the alloyed HP steels. The magnification is 225 X.

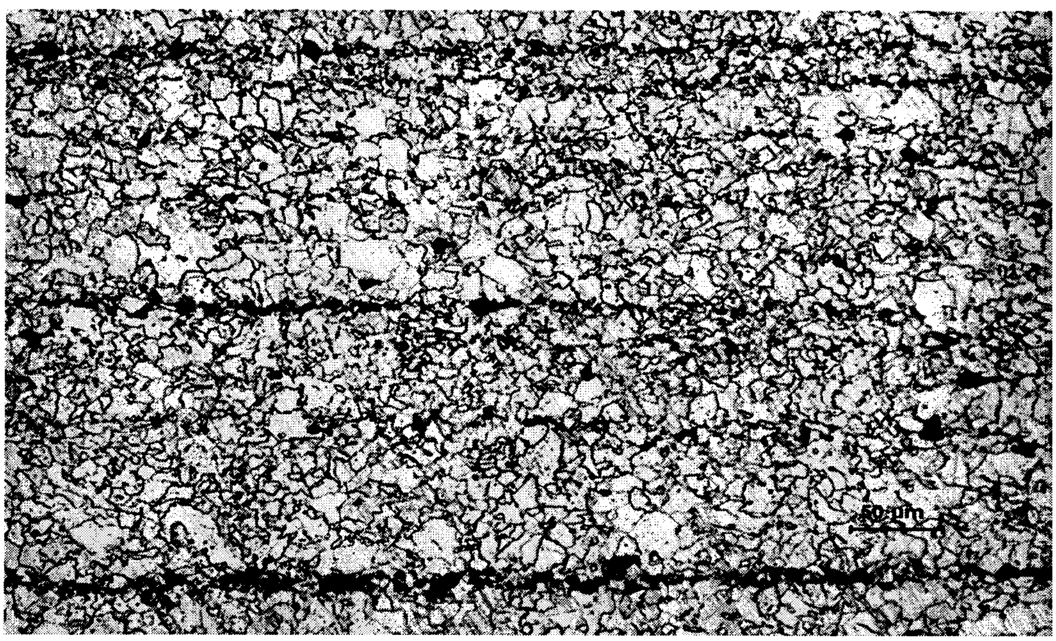

*Figure 2.* The microstructure of A710 Grade B, which is very similar to that of A709 HPS 70W, is characterized by its very fine grain size and uniform dispersion of copper-nickel precipitates throughout the ferrite matrix. The carbon contents of these steels are very low compared to A36. There is some banding of pearlite in the longitudinal rolling direction, but it is minimal compared to those in A36 plain carbon steel. The magnification is 225 X.

## 3. APPLICATION OF THIS RESEARCH

When a fabricator encounters a new material, its formability, weldability and machinability are not always evident. When it comes to machinability, fabricators may have some familiarity with similar materials, or they may rely on machine tool suppliers for advice. Such experience with each fabricator is variable. This research provides fabricators with a direct comparison of HP steels to ASTM A36, a familiar structural steel, permitting fabricators to rapidly choose cutting parameters and tooling for specific machining operations. Cutting, sawing, milling, grinding and drilling have been addressed in this research work, and the parameters established for these processes can be directly used by fabricators in their work.

By knowing what cutting tools to use, their cutting speeds, feed rates, spindle speeds, and other important factors, fabricators can select the appropriate parameters before starting any machining operations. This saves fabricators a considerable amount of experimental or "learning-curve" time. The time spent selecting cutting tools, parameters and procedures is thereby shortened, and the creation of an inordinate amount of scrap is minimized. This could also lead to decreased bid costs, since fabricators are reluctant to submit low bids on jobs that extensively use unfamiliar materials. By comparing the generally unfamiliar HP steels with A36, a material they are comfortable with, fabricators should be less inclined to sharply increase bid costs on HP steels.

## 4. SCOPE OF WORK

In this project, the Contractor, Machining Research, Inc. investigated several machining operations, using direct measurement of cutting tool wear, quality of the machined surfaces, various material factors, power consumption, and research of the known technical literature. *Machinery's Handbook* (Ref A) and the *Machining Data Handbook* (Ref B) served as a guide and starting points for identification of certain machining parameters, such as cutting speeds, feed rates, and other material factors.

### *A. Cutting and Sawing*

The surface roughness of the edges of ½ inch and 1 inch plates were measured after cutting with oxygen-acetylene and plasma. Optimal parameters were established, including the size of the tip orifice, gas pressures and flow rates, and tip travel speed. The surface roughness of the cut edge at various parameter settings was measured and recorded. A Vickers hardness profile, starting at the surface, extending inward toward the subsurface of the cut edge, was measured at each 0.005 inch to a depth of 0.100 inch or less if base metal hardness is reached after three consecutive points that have same hardness. In addition to gas cutting, band saw cutting was also included. Blades considered as optimal were evaluated, including blade speed in fpm, tooth geometry, including teeth/inch and pitch, and feed rate in in/min as a function of plate thickness. At least three proprietary or generic cutting oils for the sawing of HP steels were investigated.

### *B. Milling*

Machining Research examined the surfaces created by various cutters. The wear sustained by each cutter was evaluated by optical comparators. Cutters included 3 & 4 flute end mills and fly-cutter inserts. End mills and inserts were made of high speed steel (HSS), and HSSs coated with titanium nitride (TiN) and cobalt carbide (CoC). Sizes for end mills were ½ inch and ¾ inch. The optimal cutting speed in fpm, preferred depth of cut, spindle speed, and feed rate in ipt were determined to obtain desirable surface finishes of 500, 250 and 125 $\mu$in.

High speed steels are iron-base alloys that have carbon contents ranging from 0.8-1.4%, and have high concentrations of alloying elements which form carbides, including tungsten, molybdenum, chromium and vanadium. In the molybdenum high speed steels M34, M42 and M45, cobalt is added. Other tungsten high speed steels may have coatings of TiN. Each of these steels and their carbides are extremely hard and wear resistant, even at the elevated temperatures encountered during cutting operations. This resistance is due to the presence or the precipitation of hard carbides in solid solution at higher temperatures. The composition of the high speed steels used in this investigation and other common grades are listed in *Text Table 2.*

### *C. Drilling*

Drilling studies concentrated on comparing the appropriate feed rates and spindle rpm's for ¾ inch and 1 inch diameter annular and twist drills. The amount of drill wear was measured, as was coolant selection. Wear was compared after a specific amount of material is removed by microscopic examination of the cutting flutes. The types of drills evaluated included: high speed steel (HSS); HSS coated with titanium nitride (TiN); and various carbide drills.

*Text Table 2* / CHEMICAL COMPOSITION OF COMMON HIGH SPEED STEELS

| AISI Designation | % Carbon | % Chromium | % Molybdenum | % Tungsten | % Vanadium | % Cobalt |
|---|---|---|---|---|---|---|
| M1 | 0.78-0.88 | 3.50-4.00 | 8.20-9.20 | 1.40-2.10 | 1.00-1.35 | ... |
| M2 | 0.95-1.05 | 3.75-4.50 | 4.50-5.50 | 5.50-6.75 | 1.75-2.20 | ... |
| M10 | 0.95-1.05 | 3.75-4.00 | 7.75-8.50 | ... | 1.80-2.20 | ... |
| M34 | 0.85-0.92 | 3.50-4.00 | 7.75-9.20 | 1.40-2.10 | 1.90-2.30 | 7.75-8.75 |
| M42 | 1.05-1.15 | 3.50-4.25 | 9.00-10.00 | 1.15-1.85 | 0.95-1.35 | 7.75-8.75 |
| T-15 | 1.50-1.60 | 3.75-5.00 | 1.00 max | 11.75-13.00 | 4.50-5.25 | 4.75-5.25 |

Data source: *ASM Metals Handbook, Vol 1, Irons, Steels and High Performance Alloys* (Ref D).
"..." Indicates that there is no requirement for this element

### *D. Grinding*

Machining Research studied the grinding process, defining the cutting fluids, optimal depth of cut and feed rate in fpm. These parameters were keyed to obtaining final surface finishes of 32, 16 and 8 μin.

### *E. Turning, Tapping and Punching*

The availability of ASTM A709 HPS 70W and A710 Grade B HP steels was in plate form only. Due to fiscal restraints on this project, the machining processes of turning, tapping and punching were not evaluated, and were deferred for future research work.

However, although bars of the two HP steels were not available to determine machinability ratings by turning, the results from the other processes that were evaluated provided an ability to estimate ratings compared to other commonly used steels where there is a substantial body of data. The estimated turning machinability of the two HP steels and A36 are compared with known machinability of steels used in construction and machinery in *Text Table 6*.

## 4. CUTTING AND SAWING

All of the flame cutting operations were generally accomplished with either oxygen and acetylene, methane (natural gas) or methane-acetylene-propane (MAPP) gases. Both the flame cutting and the plasma cutting operations were performed at sites other than the facility of Machining Research, Inc. (MRI) located in Kentucky. The facilities at MRI were designed for traditional chip removal and grinding operations only. No flame or plasma cutting equipment was available at MRI. Therefore three separate trips were made to other off-site locations to monitor the oxyacetylene or plasma cutting of ASTM A36, A709 HPS 70W and A710 Grade B structural steels.

### *A. Rough Cutting of A710 Grade B Steel*

The first trip was made to the North Star Steel facility at Calvert City, Kentucky, where ½ inch thick, and 5 inch thick plates of A710 steel were furnished for testing in this contract. The A710 ½ inch thick plate was torch cut by hand since the Calvert City facility apparently had no automatic cutting equipment available. Since these plates were cut by hand, the as-cut surfaces were too rough to measure. The hand-held torch had a ½ inch O.D. with a 3/8 inch inside diameter. This torch was energized by natural gas (methane) at 95 psi and oxygen at 95 psi. The cutting rate by hand was approximately 12 ipm.

### *B. Gas Cutting of A36 Steel*

The A36 steel was purchased from the Earle M. Jorgensen, Inc. (EMJ). The steel was actually produced by Nucor Steel in Hertford, NC. The local EMJ distributor is located in Cincinnati, but the A36 steel was cut in their Cleveland warehouse where flame cutting is performed. This operation was supervised by the Cleveland Branch of EMJ, who were very cooperative with on-site observance of the cutting operations.

One inch and 2 inch thick plate sections of A36 steel purchased from EMJ were flame cut with CNC torch cutting machines. EMJ also had CNC plasma cutting machines which were used exclusively for cutting stainless steel. Two different flame cutting machines were used on the 1 inch and 2 inch plates. These CNC cutting machines were supplied with liquid oxygen, which was then converted to gaseous form at 80 psi and mixed with natural gas. The 1 inch plates were cut at 12 ipm, using a 1.0 VVC tip. This tip produced a 0.16 inch kerf. The 2 inch plates were oxyacetylene cut at 9.0 ipm, using a 1.5 VVC tip, leaving a 0.24 inch kerf. The surface roughness readings are given in *Text Table 3.*

### C. Gas Cutting of A709 and A710 Steels

The A709 steel was shipped to MRI from Missouri Fabricators located in Columbia, MO. There was no opportunity to observe any of the procedures used to cut the test pieces from the original 1 inch thick plate.

The third off-site trip was to Gusher Pumps in Dry Ridge, KY (located 31 miles south of Cincinnati, OH). This facility has an Airco CNC machine capable of either plasma or flame cutting with minimal changeover time from one type of cut to the other. A 1 inch plate of A709 was flame cut at 12 inches per minute (ipm), using a No. 4 nozzle (0.053 inch dia.). A 1 inch plate of A36 and a ½ inch plate of A710 were also cut at this condition. It was observed that this tip speed, 12 ipm, was too slow for the ½ inch plate, which was re-cut at 18 ipm. These cuts were made with oxygen gas (derived from liquid oxygen) and MAPP gas. MAPP gas is a mixture of methane, acetylene and propane, and is less explosive than pure acetylene, but less calorific value. Roughness readings for the flame cuts on all three steels are shown in *Text Table 3.*

Three plasma cuts were also made on ½ inch plates of the A36, A709, and A710 steels. All three cuts were made with the same parameters: a 400 amp nozzle at 70 ipm, drawing approximately 350 amperes. Roughness readings are shown in *Text Table 3.*

### D. Hardness Traverses of the Heat-Affected Zones

Because of the importance of the hardness of a cut edge on the machining of steels, the Vickers hardness of both flame cut and plasma cut surfaces and their heat-affected zones were measured by use of Vickers hardness indenters.

The Vickers Hardness tests were performed at the Metallurgical Laboratory of Metcut Research Associates Inc. of Cincinnati, OH. The plots of the actual Vickers hardness readings that were taken on the three steels are shown in *Figure 3* and *Figure 4*. *Figure 3* plots the hardness traverses for A36, A709, and A710 steels that were cut by plasma. *Figure 4* plots the hardness traverses for A36, A709, and A710 steels that were flame cut.

*Text Table 3* / SURFACE ROUGHNESS OF FLAME and PLASMA CUT STEELS

| Steel | Thickness, in | Cutting Method | Tip | Cutting Rate, ipm | Surface Roughness, µin |
|---|---|---|---|---|---|
| A36 | ½ | Plasma | 400 A | 70 | 86-114 |
| A709 | ½ | Plasma | 400 A | 70 | 58-115 |
| A710 | ½ | Plasma | 400 A | 70 | 103-153 |
| A710 | ½ | Flame | No. 4 | 12 | 207-214 |
| A710 | ½ | Flame | No. 4 | 18 | 160-170 |
| A36 | 1 | Flame | No. 4 | 12 | 227-249 |
| A709 | 1 | Flame | No. 4 | 12 | 85-225 |
| A36 | 2 | Flame | No. 6 | 9 | 149-232 |

NOTE: All plasma cuts were drawing 350 amps through a 400 amp nozzle.

### *E. Band Saw Cutting*

Band sawing tests were performed on all three steels. Three different types of band saw blades were used, along with three different cutting fluids. Graphic comparisons were used to: (a) analyze the effects on saw blade wear when cutting the three steels; (b) evaluate the different types of saw blades; and (c) compare various cutting fluids. Blade wear readings were taken during the progress of each test. These wear readings were the basis of analysis for the relative performance for each of the variables compared in the graphs.

In the tests comparing the three different steels, they were all performed using the same manufacturer of cutting blade (Lenox Super Plus), the same cutting fluid (Saw Master 1:10), and the same blade speed and down feed setting. All the blades were M-42 bi-metal, welded to length. A bi-metal blade is an M-42 high speed steel bonded to a spring steel backing. All the blades were designated as 5 to 8 teeth per inch, which is the inverse of the blade pitch (the distance between teeth). The blade speed was set at 120 fpm, which is the recommended speed in the *Machining Data Handbook* (Ref B).

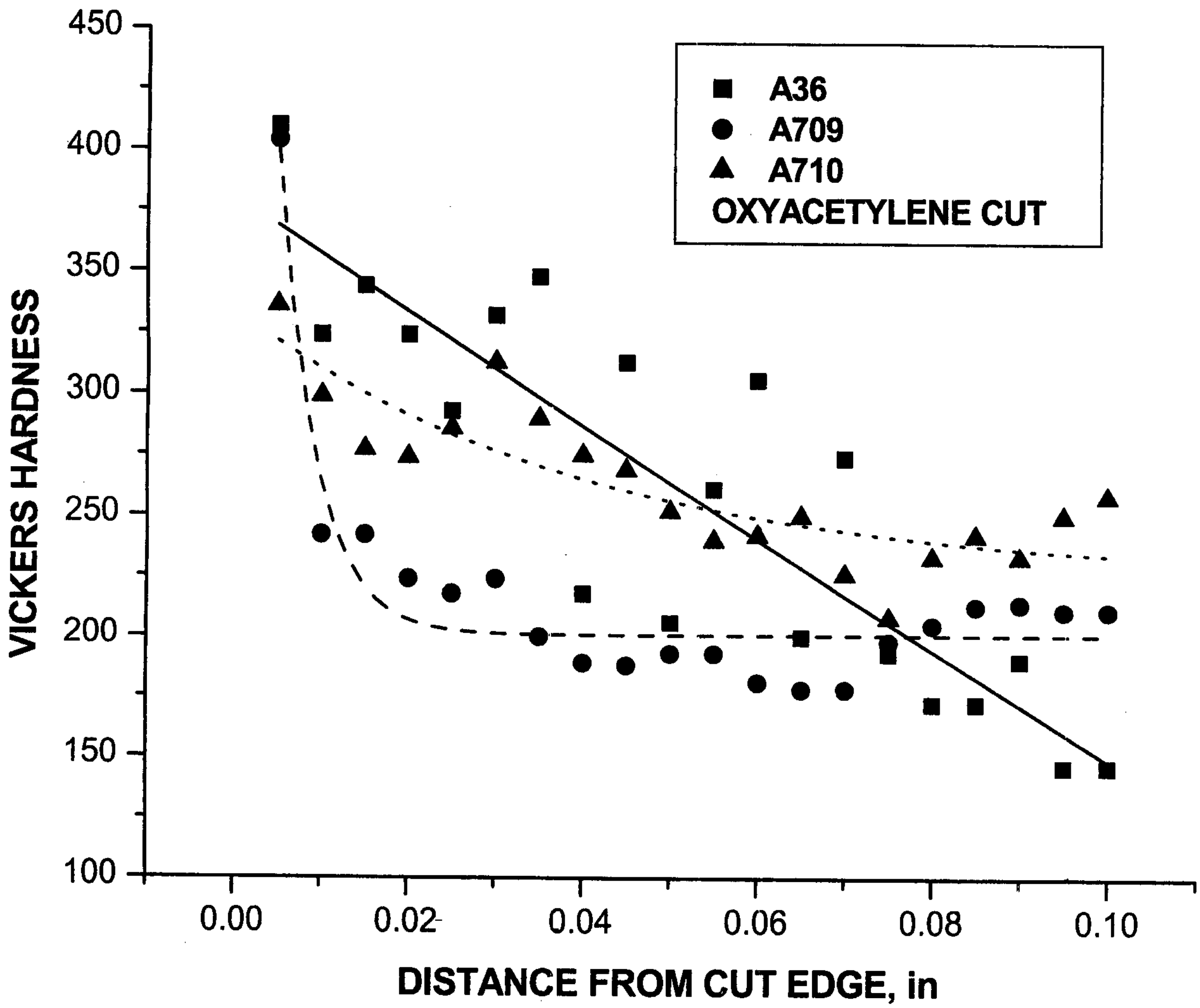


*Figure 3.* A comparison of the hardness profiles as a function of depth from the oxyacetylene cut surfaces of ASTM A36, A709 70W and A710 Grade B steels. Presumably A36 has a harder and deeper hardness profile due to its substantially higher carbon content than the HP steels, and shows wide scatter due to its larger grain size and clusters of pearlite. A709 shows base metal hardness at about 0.030" and A710 at about 0.050". A36 shows a linearly decreasing hardness to 0.100", where the traverse measurements ended. The Vickers hardness of 150 indicates a base metal tensile strength of 72 ksi, which corresponds to Rockwell B 80. This is a typical value for the tensile strength for ASTM A36 steel.

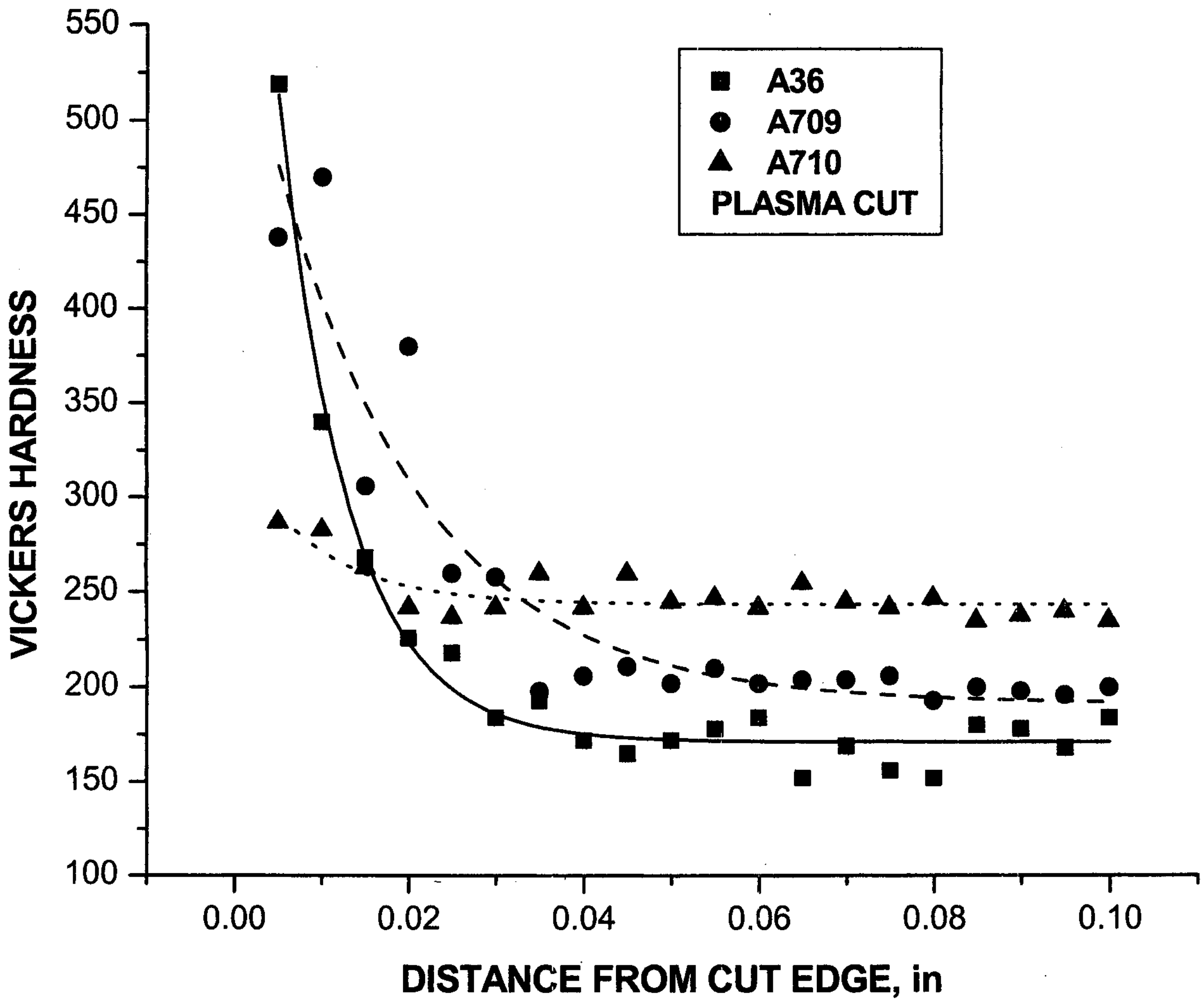


*Figure 4.* Comparison of the hardness profiles as a function of depth from the plasma cut surfaces of ASTM A36, A709 70W and A710 Grade B steels. Plasma cutting induces a slightly higher but much shallower hardness range of its heat-affected zone (HAZ) compared to oxyacetylene in A36 and A709 70W. Oxyacetylene cutting has a more diffuse distribution of heat than plasma. Presumably A36 has higher peak hardness due to its substantially higher carbon content. A709 HPS 70W, because of its quench-hardenability, has a steep but shallow HAZ. A710 Grade B has no additional chromium to its list of alloying elements that contribute to its hardenability, which probably accounts for its lesser peak hardness.

*Figures 5 and 6* show the relative machinability of the three HP steels in band sawing. *Figure 5* shows the blade wear as a function of the material sawed, measured in square inches. *Figure 6* is a similar plot, showing the same blade wear as a function of total time of the blade in the cut. In both of these plots, the A709 steel has the lowest blade wear (or the best machinability) in band sawing. There is not a great deal of difference between the A36 steel and the A710 steel, although the A36 steel appears to have slightly less machinability than the A710 steel.

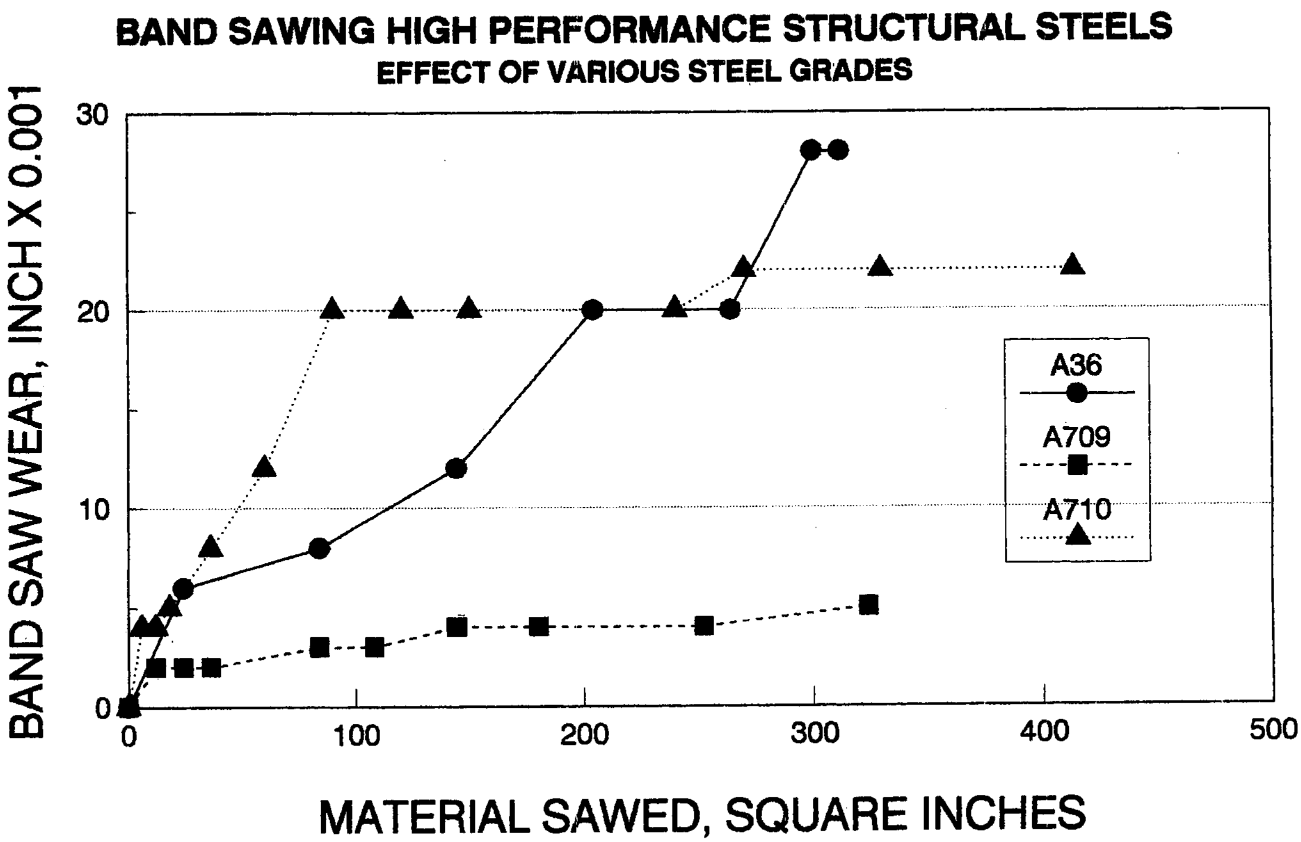


*Figure 5.* In terms of band saw wear, the A709 HP 70W steel sustained the least blade wear based more than 300 in$^2$ sawed. The saw blade wear for A710 Grade B was only slightly less than that of A36 steel.

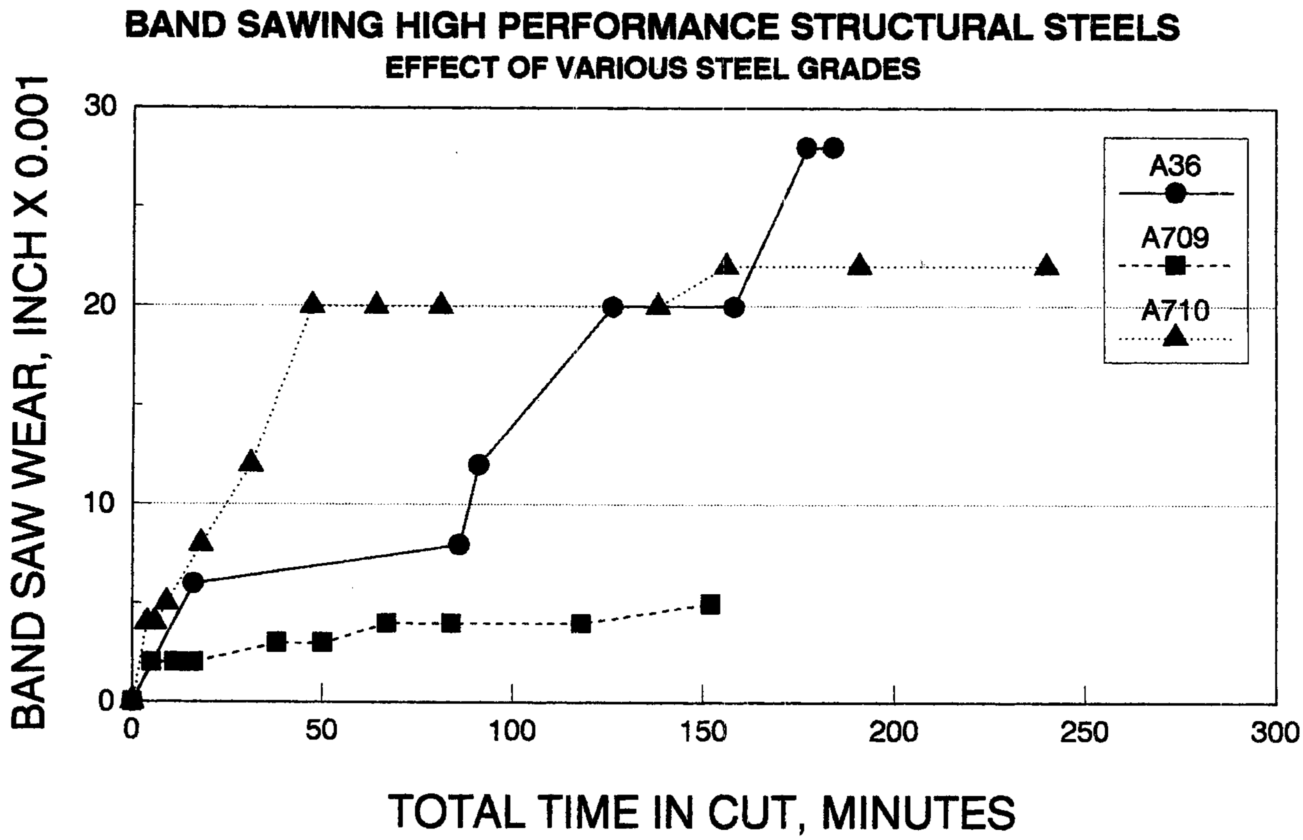


*Figure 6.* Based on total time in cut in minutes, the A709 HP 70W steel sustained the least blade wear. After an initial jump in wear after about 40 minutes, the blade sawing A710 Grade B stabilized, whereas wear on A36 steel blade continued to climb in a somewhat jagged linear fashion after 70 minutes in cut.

Since the HP steels had better sawing performance, Machining Research selected A36 to compare different cutting fluids for the worst case. *Figures 7* and *8* show the influence of three different types of cutting fluids used to band saw the A36 steel. The Mobil Gamma oil produced lower blade wear than either of the water soluble fluids. This result is expected, as a straight oil product is usually better than water soluble products when cutting with high speed steel tools.

If you compare *Figures 7* and *8* at a blade wear level of approximately 0.020", you observe that both water base fluids cut close to the same amount of material, about 275 square inches, but the material cut with Trim Sol® was in much less time than with Saw Master®, indicating a more effective performance for the emulsion type (Trim Sol®) of fluid than the synthetic (Saw Master®) type of fluid.

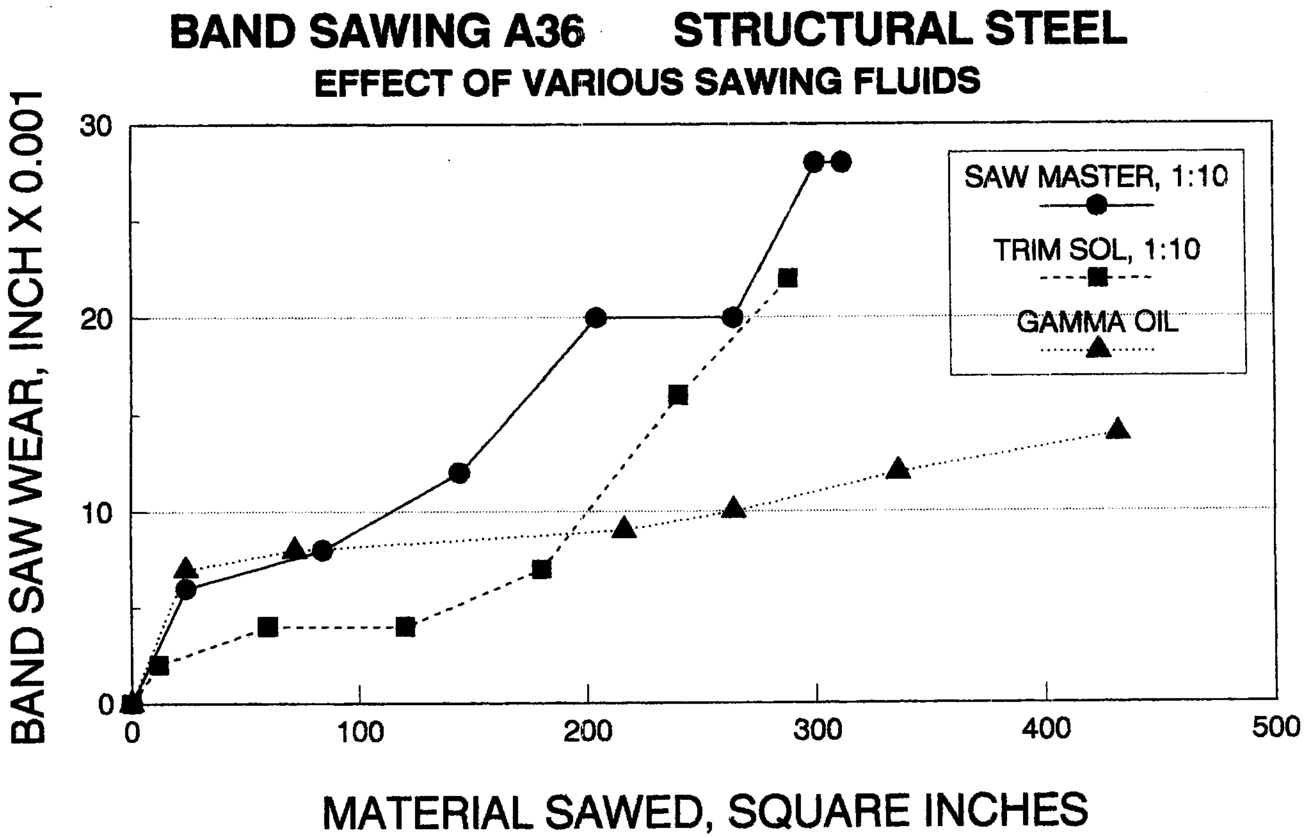


*Figure 7.* Cutting oil provided the least amount of wear for saw blades in terms of square inches of area sawed compared to water soluble oils when cutting the A36 plain carbon steel. Trim Sol® (Ref E) is a water soluble emulsion cutting and grinding fluid, and Saw Master® (Ref F) is synthetic water soluble oil. Concentrations of 7% or more water soluble oil are recommended for better sump life.

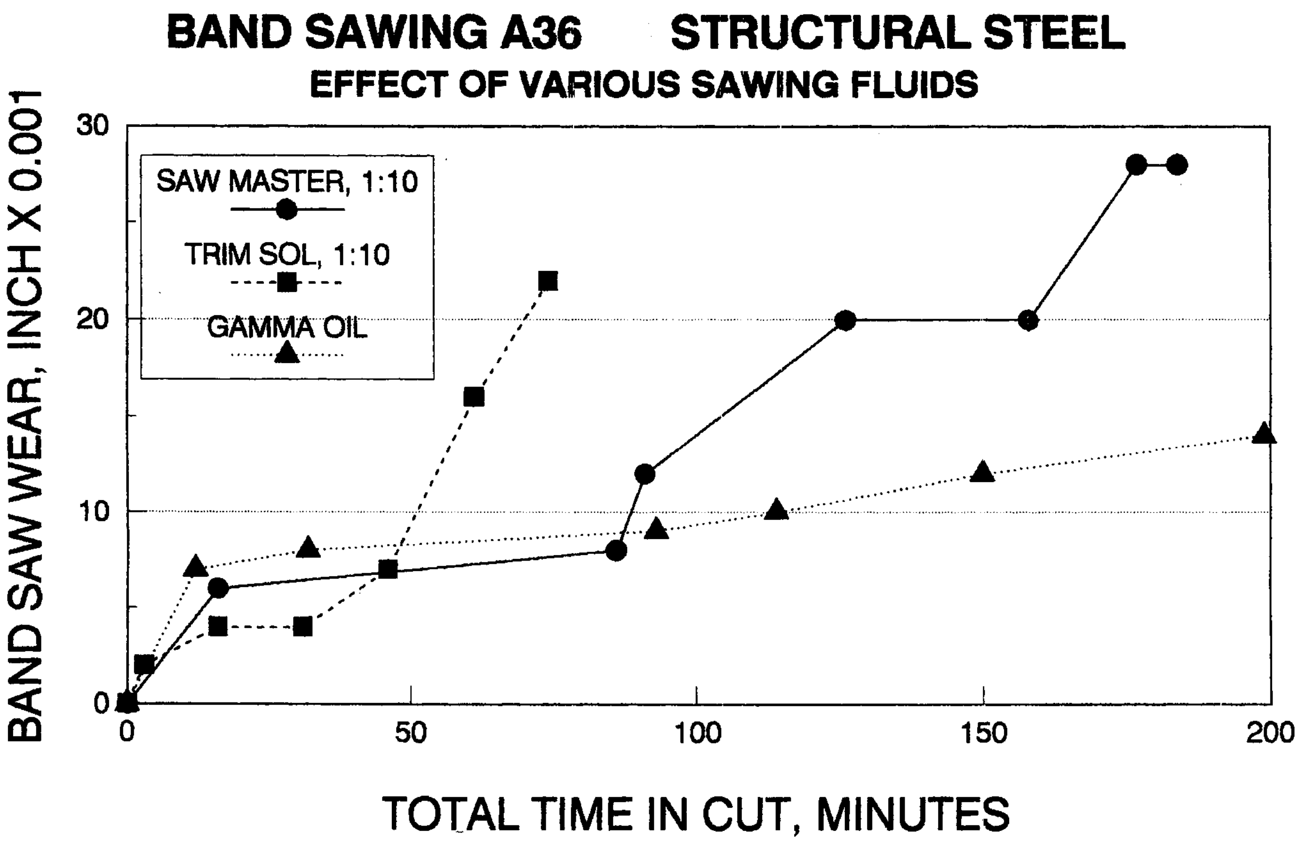


*Figure 8.* The comparison of wear on saw blades based on time in cutting A36 carbon steel. Results are similar to amount of area sawed, except that use of the synthetic water soluble oil incurs less wear on blades than the emulsion cutting oil over time. The straight cutting oil continues to sustain a relatively flat increase in blade wear even after 150 minutes in cut.

*Figures 9* and *10* show the performance of three different types of band saw blades when cutting A36 steel. The RX and the Super Plus blades were recommended by Lenox, a division of American Saw and Manufacturing, for the band sawing of A36 steel. The Lenox RX blade had the lowest blade wear of the three types of blades. The Lenox Super blade had the greatest blade wear.

The Lenox RX blade was primarily engineered to cut structural shapes. The blade is typically made of high speed steel and the teeth are coated with an aluminum-titanium-nitrogen (AlTiN) compound to provide long blade life. The Lenox Super and Super Plus blades are of bi-metal composition, having M-42 high speed steel teeth hardened to 67-69 Rockwell C, with high carbon spring steel as a backing material.

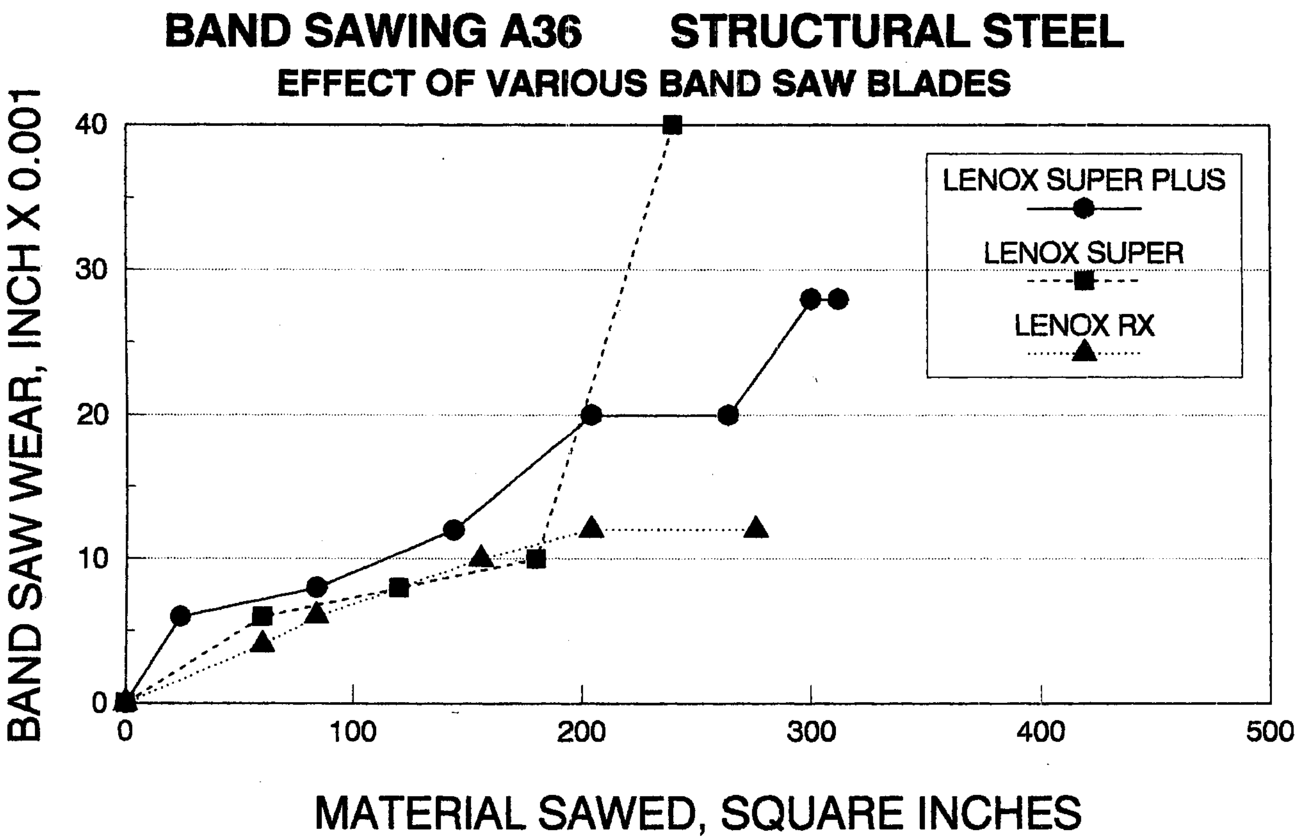


*Figure 9.* The effect of three different saw blades on the band sawing of A36 carbon steel. The Lenox RX sustained the least amount of blade wear after more than 270 $in^2$ of area sawed. In comparison, the Lenox Super had more than double the amount of wear at 270 $in^2$, whereas the Lenox Super Plus sustained a very sharp increase in blade wear between 200 to 240 $in^2$ of cut surface.

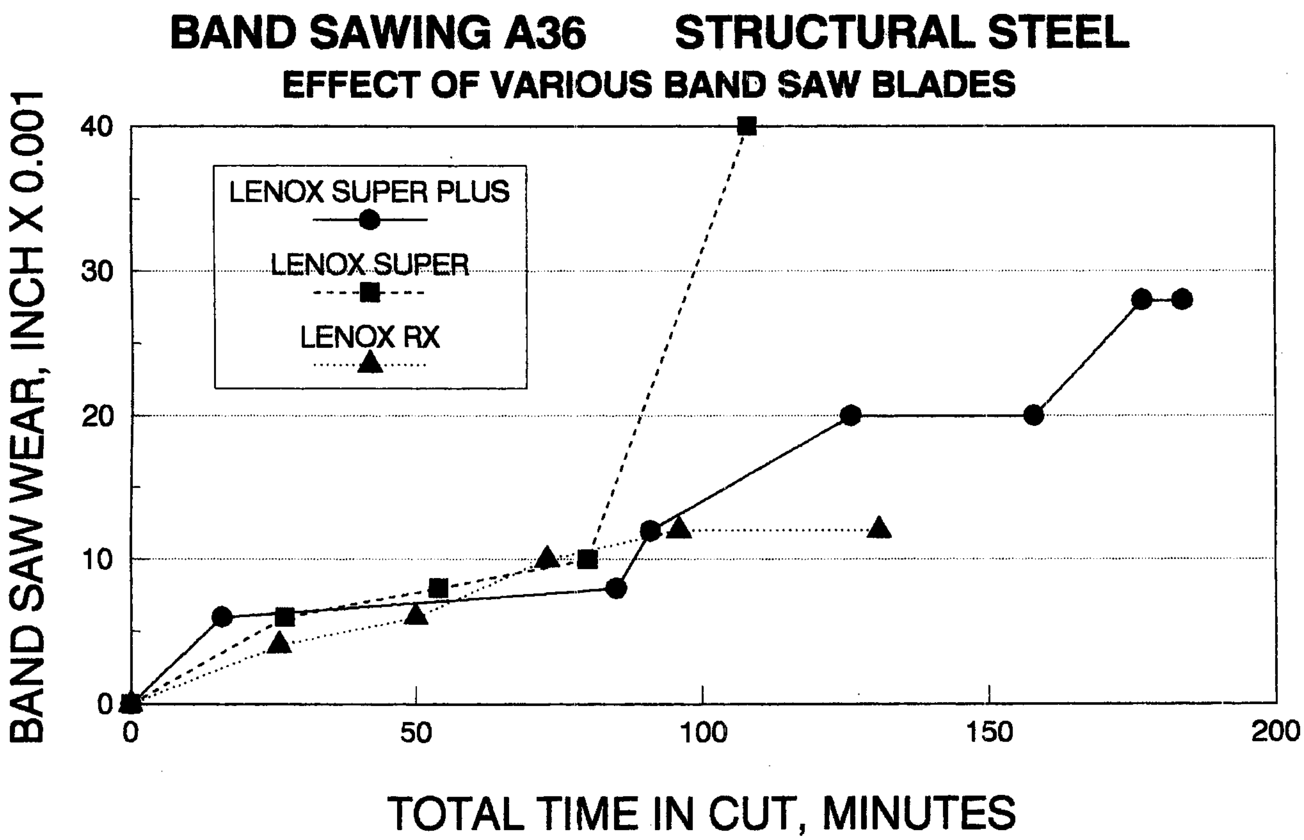


*Figure 10.* The band sawing of A36 carbon steel reflects similar results as determined by amount of area sawed. The Lenox RX blade sustained the least wear after 130 minutes of cutting, whereas the Lenox Super almost doubled blade wear. The Lenox Super blade effectively began to terminate its cutting ability in between 75 to 110 minutes of service.

## 6. FACE AND END MILLING

The milling portion of this project was divided into face milling and end milling. The work materials remained the same at A36 steel plate at 156 BHN, A710 steel plate at 229 BHN and A709 HPS 70W steel plate at 229 BHN. The face milling tests were performed on a three-axis, Tongil Computer Numerically Controlled (CNC) Machining Center, which was equipped with a 20 hp spindle drive.

### *A. Tool Materials and Test Conditions*

For fly-cutting, indexable solid carbide inserts are used. The SNMG designation is an ANSI Standard Code for a particular geometry and composition of indexable carbide inserts. The first letter indicates the shape of the insert: "S" indicates square, "D" is diamond-shaped, "K" is a parallelogram, "R" is round, "T" is a triangle, and "V" is v-shaped. There are several other letter symbols for shape. The second letter is the relief angle, where "N" is zero, "P" is 11°, and letters "A" through "G" progress from 3° up to 30°. The third letter is the tolerance class. The fourth letter is the type of insert, indicating whether it has a hole, or is without a hole, has a chip groove or has combinations of each variation. The "G" designation used in this study has a hole with a chip groove on the both top surfaces. The first number is the size class, the second the thickness and the third number the cutting point configuration. A "432" insert has a corner radius of 1/32 inch. Negative rakes are generally recommended, since they better support the insert, making them less susceptible to breakage or chipping. Positive rakes are used where the materials are long or thin-walled items made of free-cutting alloys, like leaded brasses or various aluminum alloys.

High speed steel (HSS) inserts for this type of cutter are rarely used. Face mills or fly cutters are equipped with indexable carbide inserts, similar to those used in a turning operation. If the speed capacity of the machine tool is too slow to accommodate carbide cutters, then a HSS shell end mill, which is essentially a short, multi-flute, large diameter HSS end mill should be used to mill a wider surface.

The work pieces were clamped in two 8 inch Kurt heavy duty milling vises, which are keyed and bolted to the table of the machining center for maximum rigidity.

### *B. Fly Cutting*

The cutter used in these tests was a 4 inch diameter, 5 tooth indexable insert face mill. Four of the inserts were removed to create the single-tooth "fly cutter" effect required in this contract. A 4 inch diameter, 5 tooth face mill with only one insert clamped in was used as the fly-cutter. The inserts used in this fly-cutter were made by Mitsubishi, a TiN coated carbide SNMG-433 style, which is ½ inch square by 3/16 inch thick with a 3/16 inch nose radius, and has a negative rake.

The insert used in these tests was Mitsubishi Grade US735 micro-grain carbide coated with titanium nitride, in SNMG-433 style. The micro-grain carbide "core" of the insert is a very tough grade of carbide that resists edge chipping when subjected to the interrupted cuts in face milling. This is a ½ inch square, negative rake insert with 8 usable cutting corners. The insert is 3/16 inch thick and has a 3/64 inch nose radius with a moderate chip control configuration. The number-three 3/64 inch nose radius was a major contributory factor in producing the exceptionally smooth surfaces recorded. The "chip control" configuration is intended to break continuous or stringy chips often encountered in turning or boring operations. Chip control is usually not a problem with face milling, which is an interrupted-cut machining operation.

These tests were conducted dry without a cutting fluid. Tool life is typically longer without a cutting fluid than it is when using a water-base fluid in face milling steel with carbide or coated carbide inserts. The interrupted cutting sequence creates severe thermal shock to the cutting tool using a water-based cutting fluid. Oil base fluids are unsuitable since the cutting speeds are usually high causing the oil to smoke, creating an unfavorable (smoky/smelly) environment for the machine operator.

The ability to use a face mill to shape a part to print dimensions and produce a smooth surface finish is very useful in eliminating the additional step of grinding. Eliminating an additional manufacturing step reduces cost and should increase productivity. Except for unusual situations, where surfaces are deliberately "rough", such as to hold a gasket in place, most finishes are 64 µin or lower. A finish requirement of 125 µin or higher on a print usually indicates that the finish is not critical in the use of the manufactured part. There is often a correlation between the surface roughness required and the dimensional tolerance. Many sensitive profilometers used for measuring surface roughness do not record finishes of 200 µin or higher, and typically give an error reading on very rough surfaces.

The results of surface roughness tests on the A36, A709 HPS 70W and A710 Grade B HP steels are listed in the Appendix in *Data Table 1*. The axial depth of was 0.050 inch, with a radius of cut of 2.0 inch, in a down milling set up. Data are plotted in *Figure 11* and *Figure 12*. *Figure 11* shows the effect of cutting speed on surface roughness. The smoothest finish of 28 µin was obtained at the cutting speed of 500 fpm. *Figure 12* shows the effect of feed rate on surface roughness at two cutting speeds, 500 and 900 fpm. *Figure 12* shows that the higher speed of 900 fpm was much more effective in producing fine or smooth finishes. Readings in the range of 19 to 23 µin were obtained, which is a good finish.

Down milling, also designated as climb milling, was used throughout this investigation. Down milling produces thicker chips, permitting substantial heat transfer. Increased heat transfer promotes increased tool life, whereby there is less chance for chip wedging or seizure. Cutters press the work piece downward, minimizing vibration and improving surface finish. Feed power consumption is lower, and chips are ejected downward, presenting less of a hazard to operators. There is less sideward deflection, thereby increasing the possibility of increased feed rates.

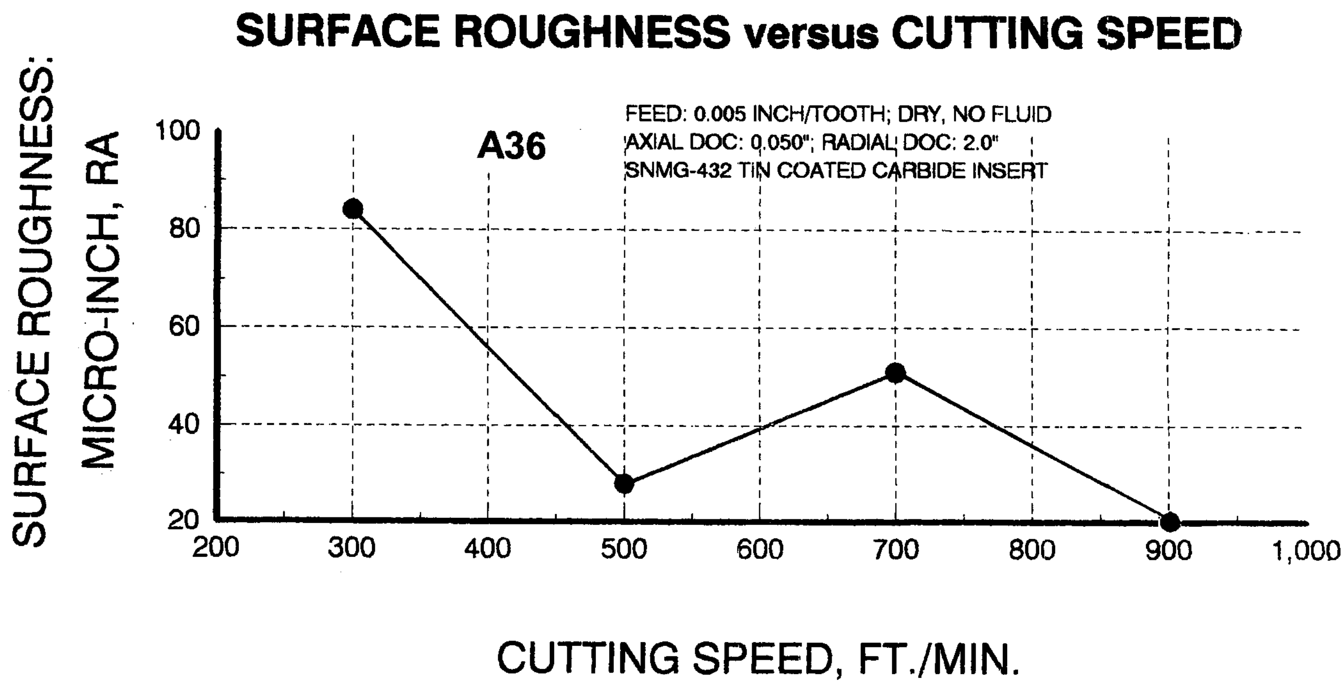


*Figure 11.* The surface roughness of face-milled ASTM A36 steel at 156 Brinell Hardness (82 Rockwell B) was at a minimum of 23 μin at 500 fpm cutting speed when fed at a rate of 0.005 ipt.

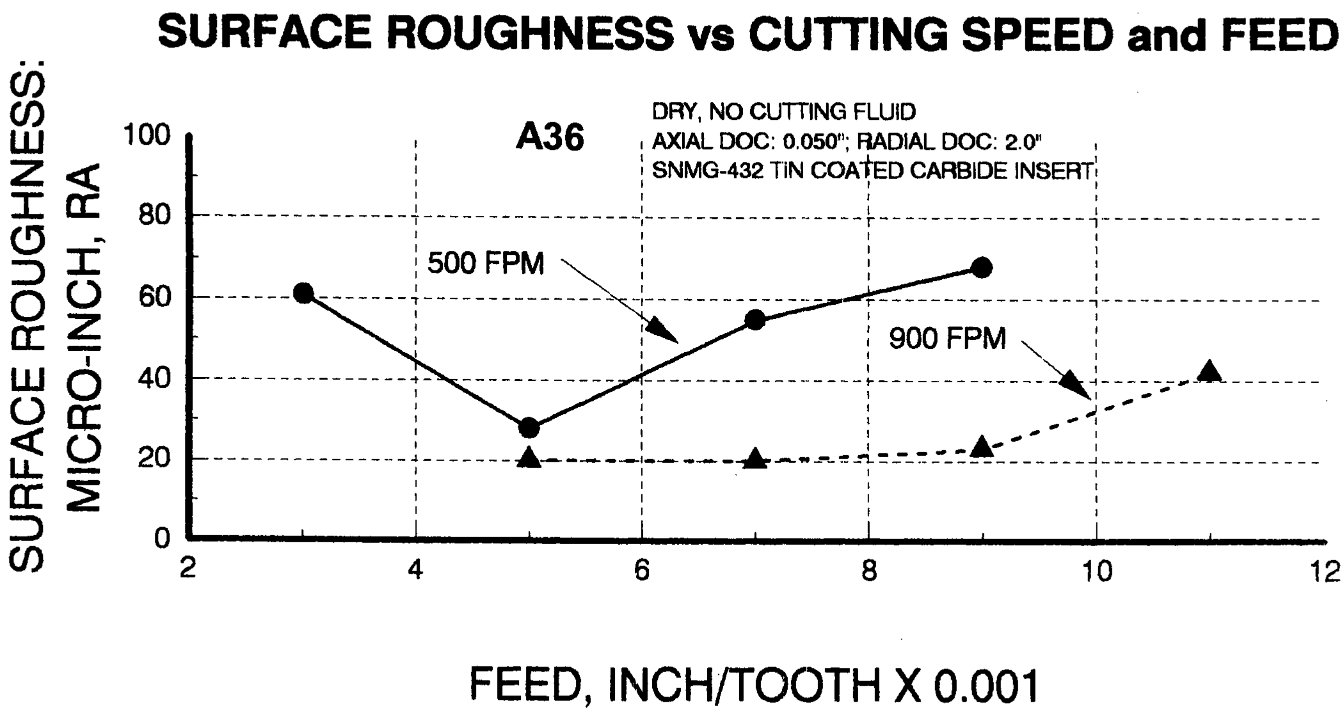


*Figure 12.* The comparison of feed rates from 0.002 to 0.012 ipt with cutting speeds at 500 and 900 fpm for the face milling of ASTM A36 steel. At 500 fpm, the best surface finish is at a rate of 0.005 ipt. For 900 fpm, a range of 0.005 to 0.009 ipt provides a surface finish of about 20 μin.

*Appendix Data Table 1* lists the results of the surface roughness tests on A709 steel. *Figures 13* and *14* are plots of these data. The smoothest surface reading was 11 µin at 500 fpm and 0.003 ipt. Surface roughness readings of 14 µin were also obtained at feed rates of 0.005 ipt and 0.007 ipt. For A709, the smoothest finishes were obtained at 500 fpm, unlike A36 steel where 900 fpm was the best cutting speed.

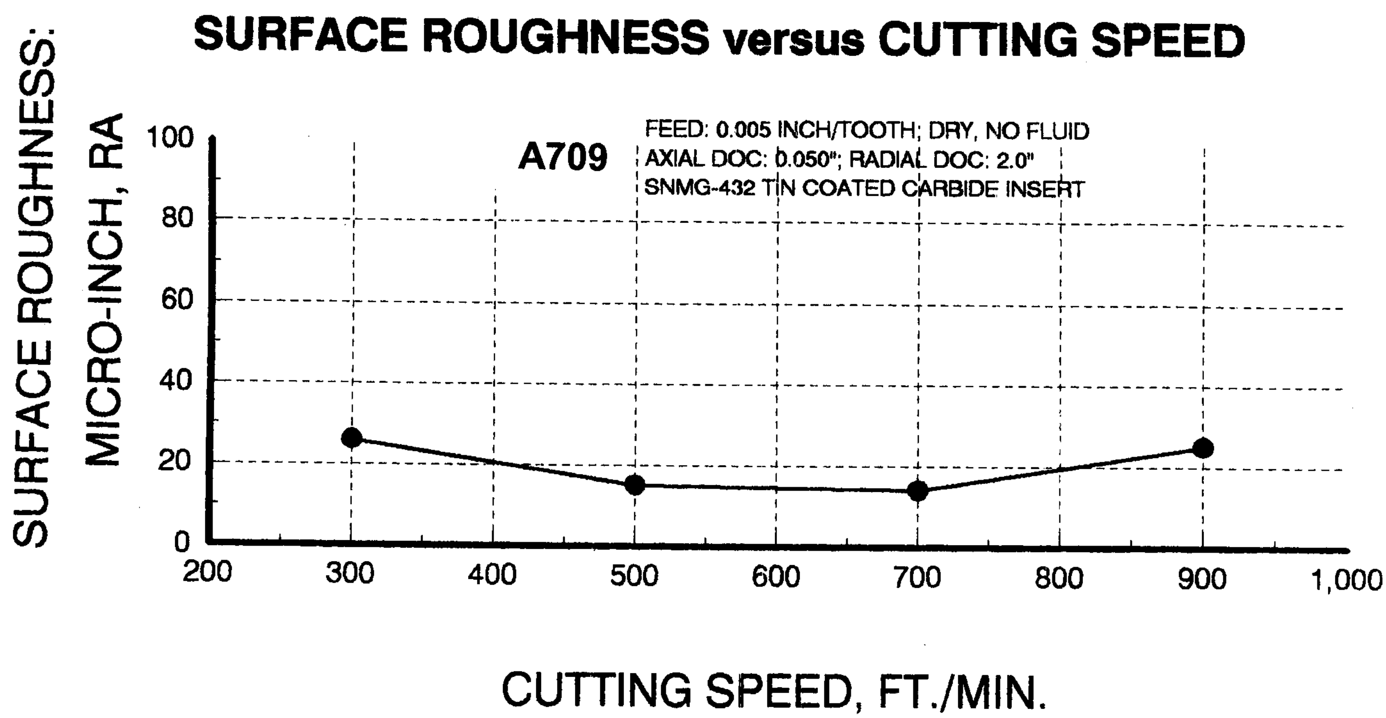


*Figure 13.* The best surface finishes obtained from face milling of ASTM A709 HPS 70W steel at 229 BHN (98 Rockwell B) were at a cutting speed range of 300 to 900 fpm, with the optimum speeds at 500-700 fpm. Surface finishes were comparable to those obtained by grinding.

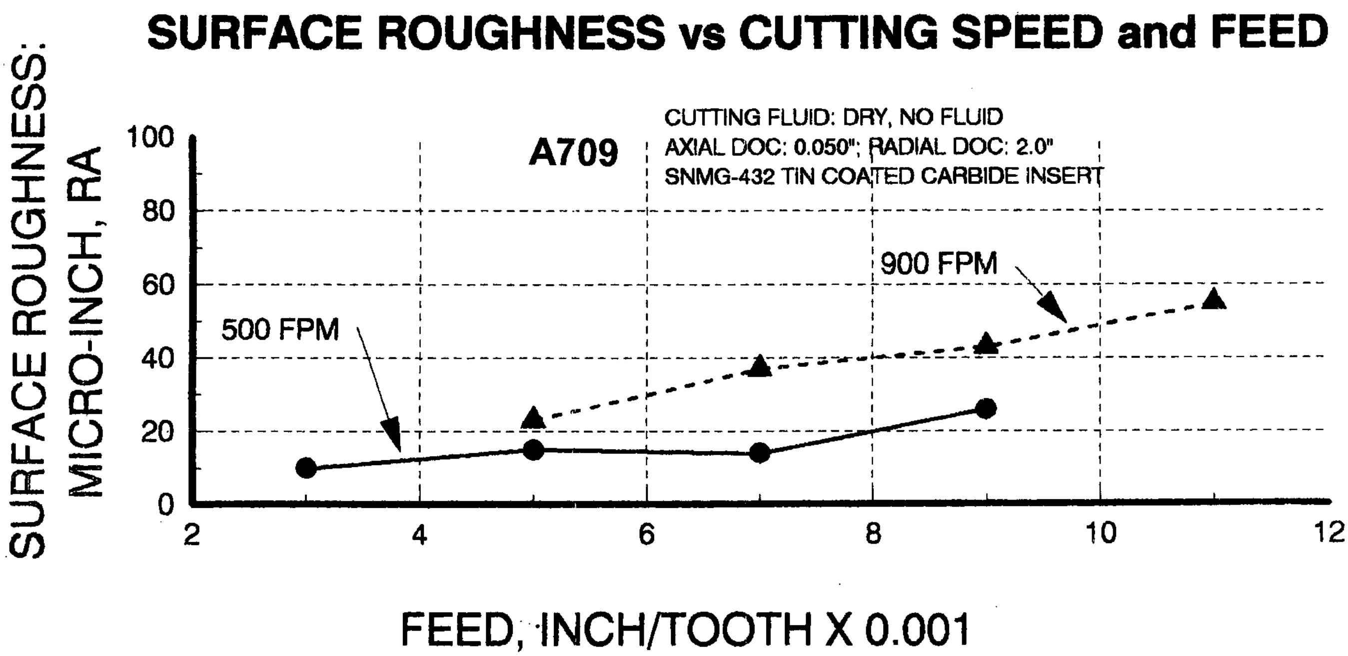


*Figure 14.* The best surface finishes were obtained by face milling ASTM A709 HP 70W steel when the feed rates were at 0.003-0.007 ipt at 500 fpm. Surface finishes were in the range of 10-15 µin at this feed rate. At 900 fpm, surface finishes become twice as rough when feed at rates exceeding 0.005 ipt compared to those at 500 fpm.

The surface roughness readings obtained on the A710 steel are listed in *Appendix Data Table 1*. Four combinations of speed and feed produced finishes of 7 to 8 µin, which are as good as or better than most finishes produced by surface grinders. In our grinding study on these three steels, surface roughness readings of 4 to 5 µin were obtained. These finishes are usually obtained by polishing with 600 grit paper after grinding. Milling finishes this good are usually even more difficult to obtain on soft steels, such as the A36 at 156 BHN, even though A709 and A710 steels are not considered "hard" at 229 BHN.

*Figure 15* shows roughness readings of 7 to 8 μin, which are considered to be excellent finishes at 700 to 900 fpm. *Figure 16* shows the relationship between surface roughness and cutting speed and feed rate for A710 steel.

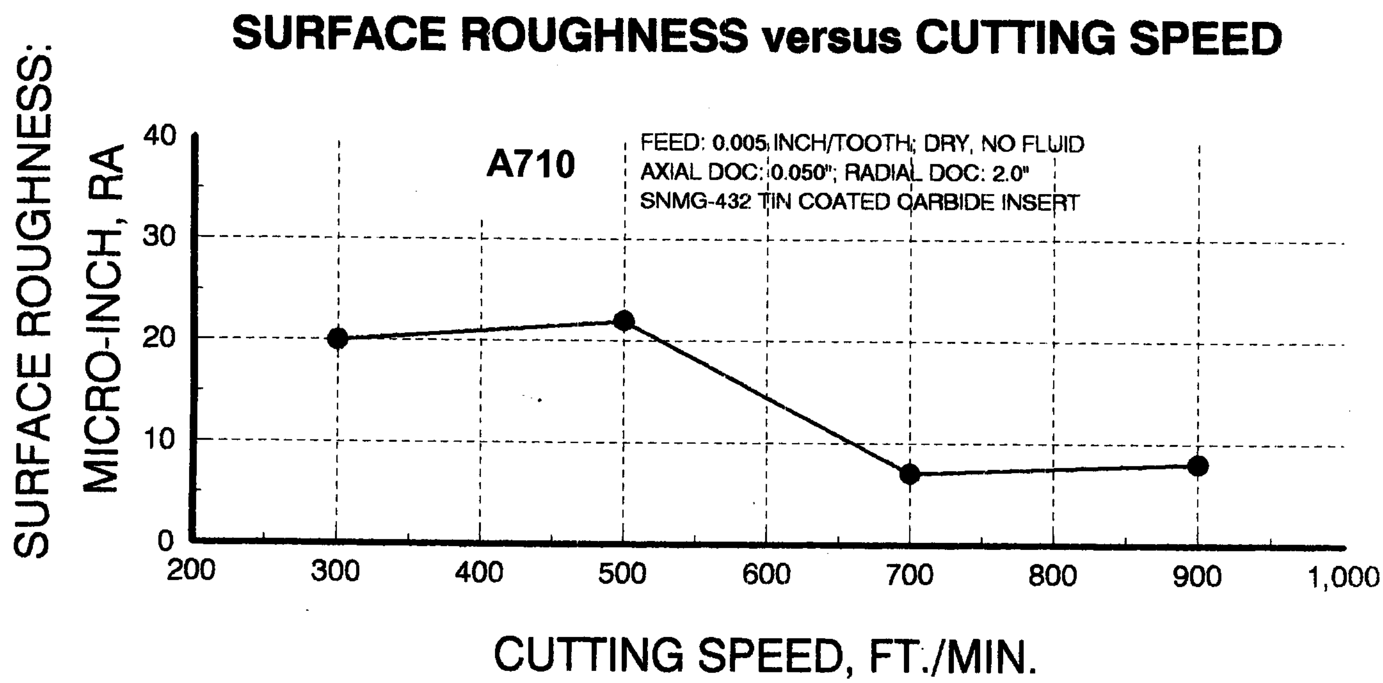


*Figure 15.* The face milling of ASTM A710 Grade B steel at 229 BHN (Rockwell B 98) revealed that the cutting speed range of 700 to 900 fpm provided surface finishes of 7-8 μin, comparable to those obtained by grinding.

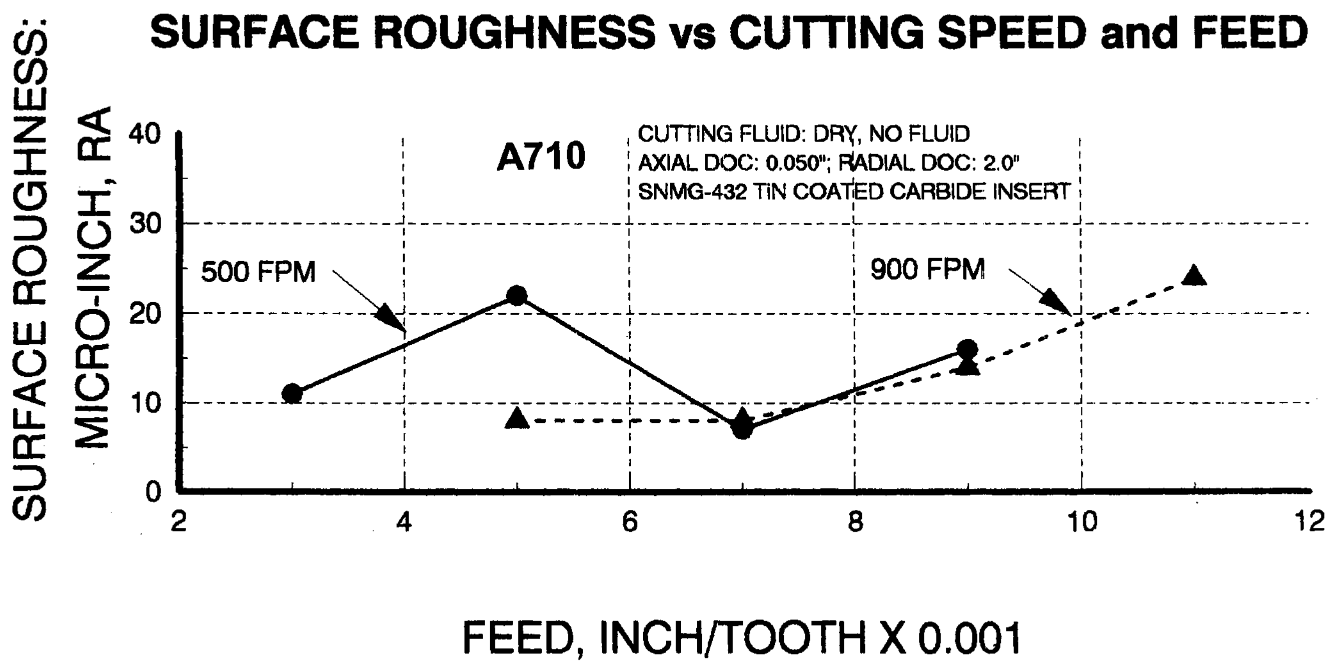


*Figure 16.* The optimum surface finishes of less than 15 µin were obtained by face milling ASTM A710 Grade B steel at 900 fpm with a feed rate ranging from 0.005 to 0.009 ipt. At 500 fpm, similar surface roughness readings were found at a narrower range of 0.007 to 0.009 ipt.

*Figures 17, 18,* and *19* compare all three steels at different combinations of cutting speed and feed rate. *Figure 17* shows no consistent pattern of surface roughness advantage of one steel over the other two within the range of 300 to 900 fpm at 0.005 ipt. In *Figure 18,* the A709 and the A710 steels produce better finishes than the A36 steel at 500 fpm. The A710 steel provided consistently lower roughness readings (smoother finishes) over the entire range of feed rates at 900 fpm as shown in *Figure 19.*

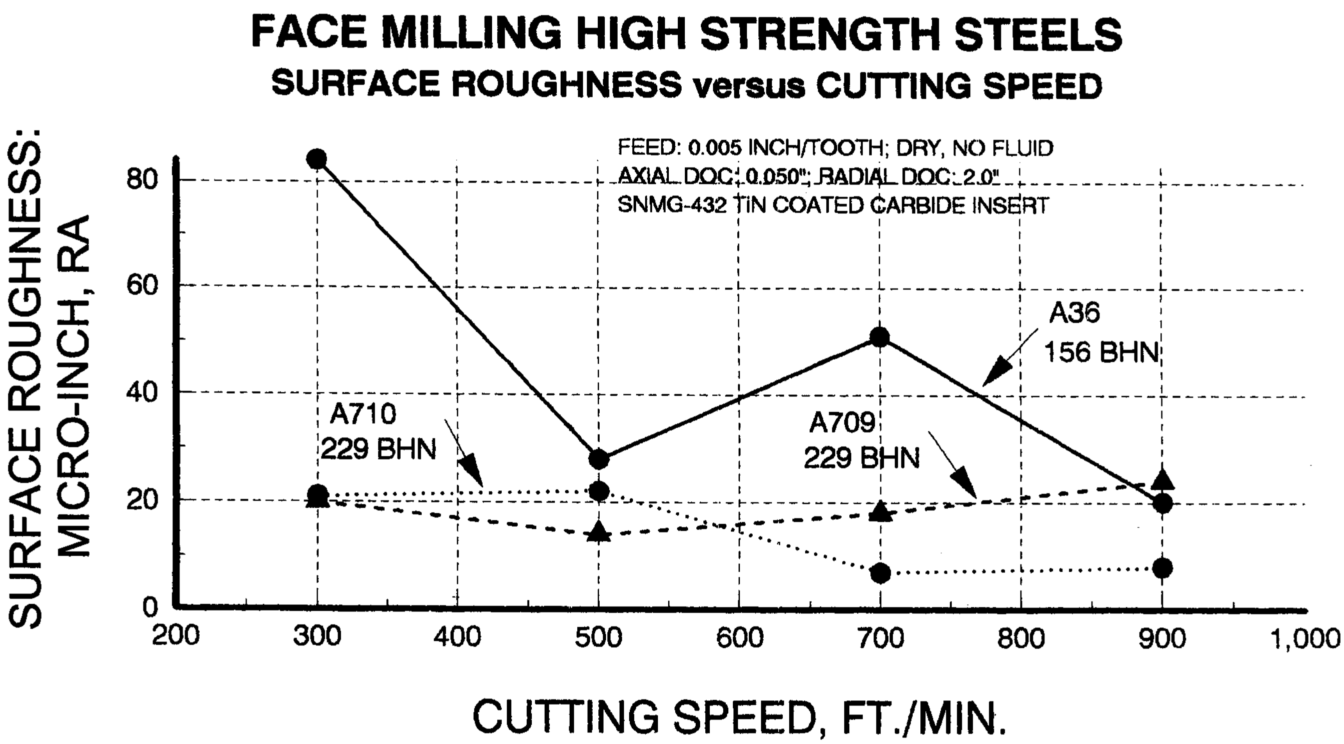


*Figure 17.* The comparison of three steels and their surface finishes obtained by face milling at different cutting speeds. Except for a very narrow range of cutting speeds at 500 and 900 ipm, A36 steel has a machinability rating of 50% less than the HP steels. If A36 is given a machinability rating of 50%, based on Ryerson machinability ratings for SAE1020, the estimated machinability for the two HP steels is about 80% of SAE 1212 for face milling.

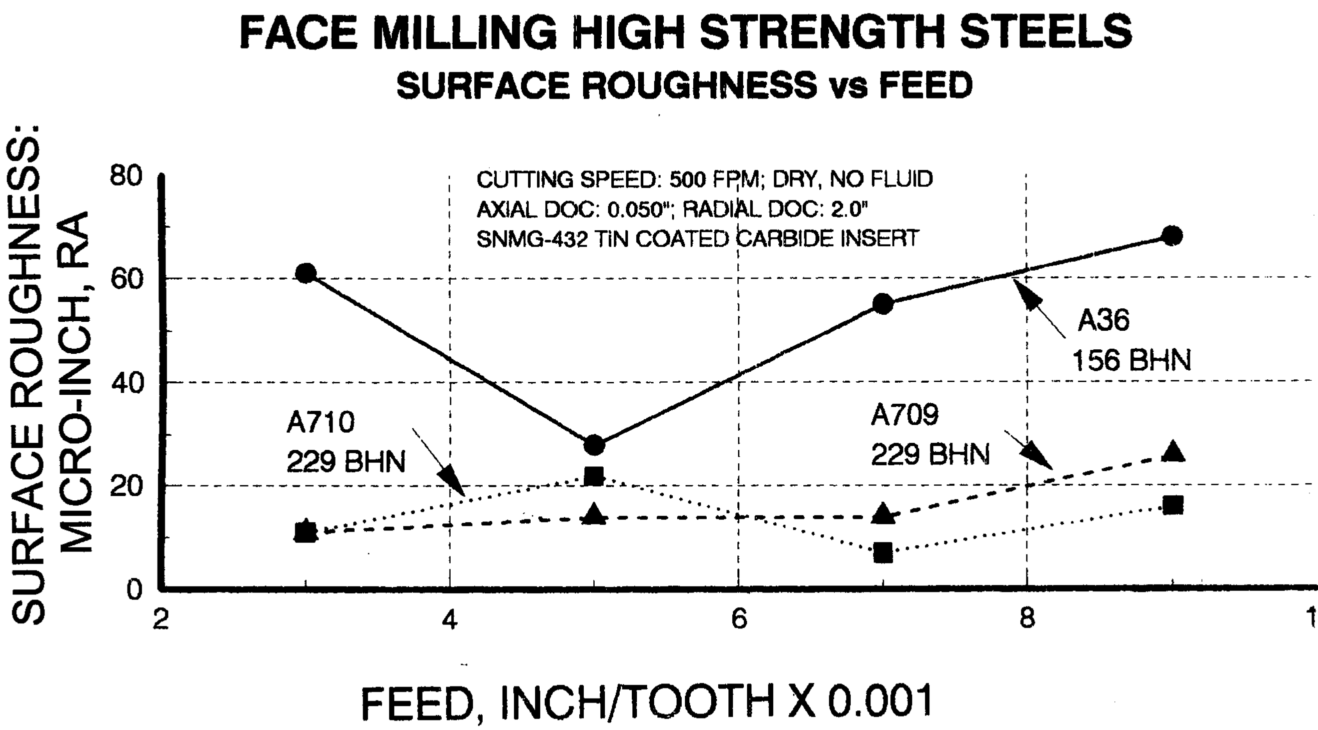


*Figure 18.* The comparison of machinability of the two HP steels with A36 based on feed rates at a cutting speed of 500 fpm. In general, except for the narrow range at 0.005 ipt, ASTM A36 has a machinability rating when based on surface roughness of about 33% of the HP steels.

*Appendix Data Table 2* shows the rate of tool wear and its effect on surface roughness as cutting time increases to tool failure, as defined by a tool wear limit. The traditional end points for tool life testing of carbide or coated carbide inserts are 0.015 inch of uniform or average wear or 0.030 inch of localized or peak wear, whichever condition occurs first.

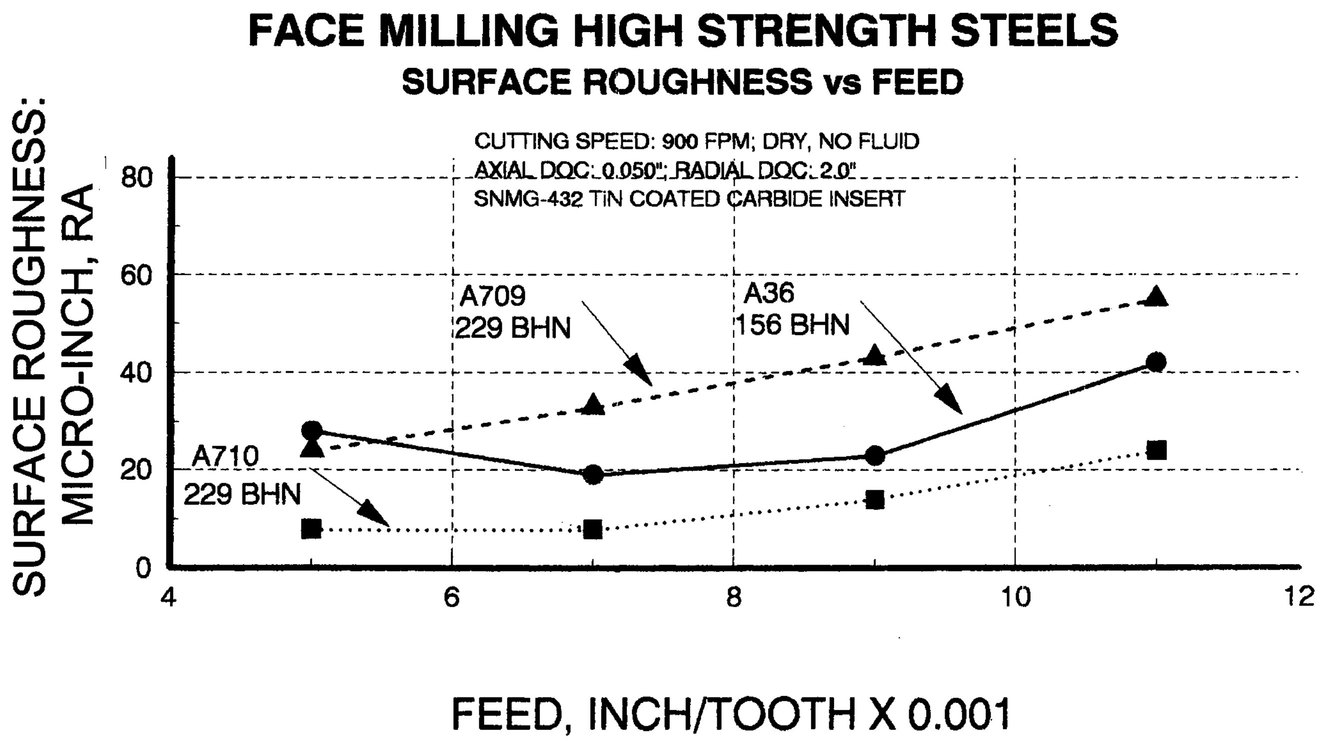


*Figure 19.* The comparison of face milling machinability of the two HP steels with A36 based on feed rates at a cutting speed of 900 fpm. In sharp comparison to cutting speeds at 500 fpm, ASTM A36 has a machinability rating when based on surface roughness that is equivalent to the HP steels. When properly set at the correct feed rates and cutting speeds, each of these steels have comparable machinability ratings and provide good-to-excellent face milled surface finishes.

*Figure 20* summarizes the effect of cutting time on uniform tool wear for all three high strength structural steels. Perhaps the influence of material hardness is shown here, because for the softer A36 steel is cut longer by approximately 5 minutes than the A709 or the A710 steels for the same amount of tool wear at 0.015 inch. There is very little difference between the tool wear rates of the A709 and the A710 steels.

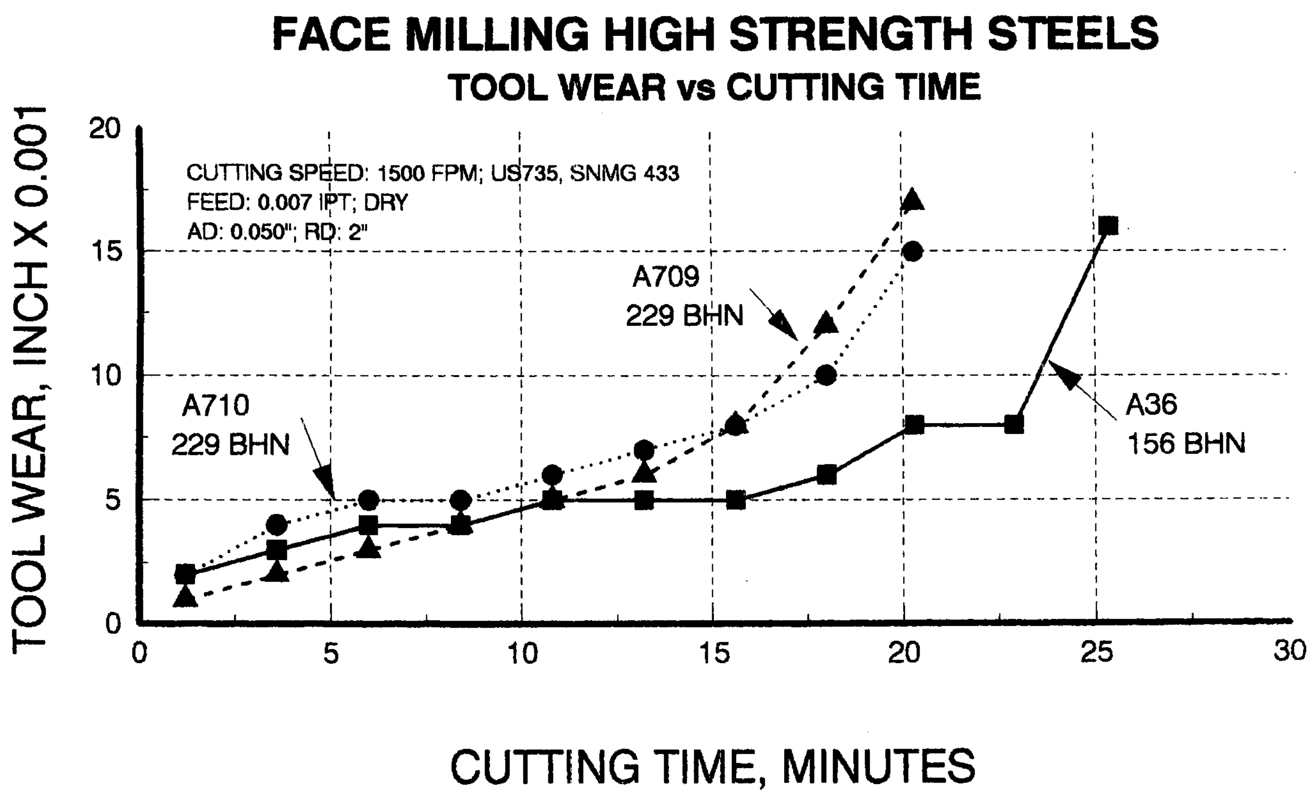


*Figure 20.* At a cutting speed of 1500 fpm, each of the three steels experience the same rate of tool wear up to about 12 minutes of operating time. Afterwards, the HP steels sustain a sharp increase in rate of wear, whereas the A36 rate spike is delayed for another 5 minutes. The increased wear rate is attributed to the harder and continuous ferrite matrix in both the A710 and A709 steels compared to the softer A36 steel at 159 BHN.

*Figure 21* shows the influence on surface roughness as cutting time and therefore tool wear increased. Both the A709 and the A710 steels show sharp increases in roughness readings when the tool wear reached its end point, while the A36 steel did not. This difference is somewhat surprising since the A36 steel showed a sharper increase in tool wear in *Figure 20.* The surface roughness of the A36 steel had little variation over the entire cutting time of 25 minutes.

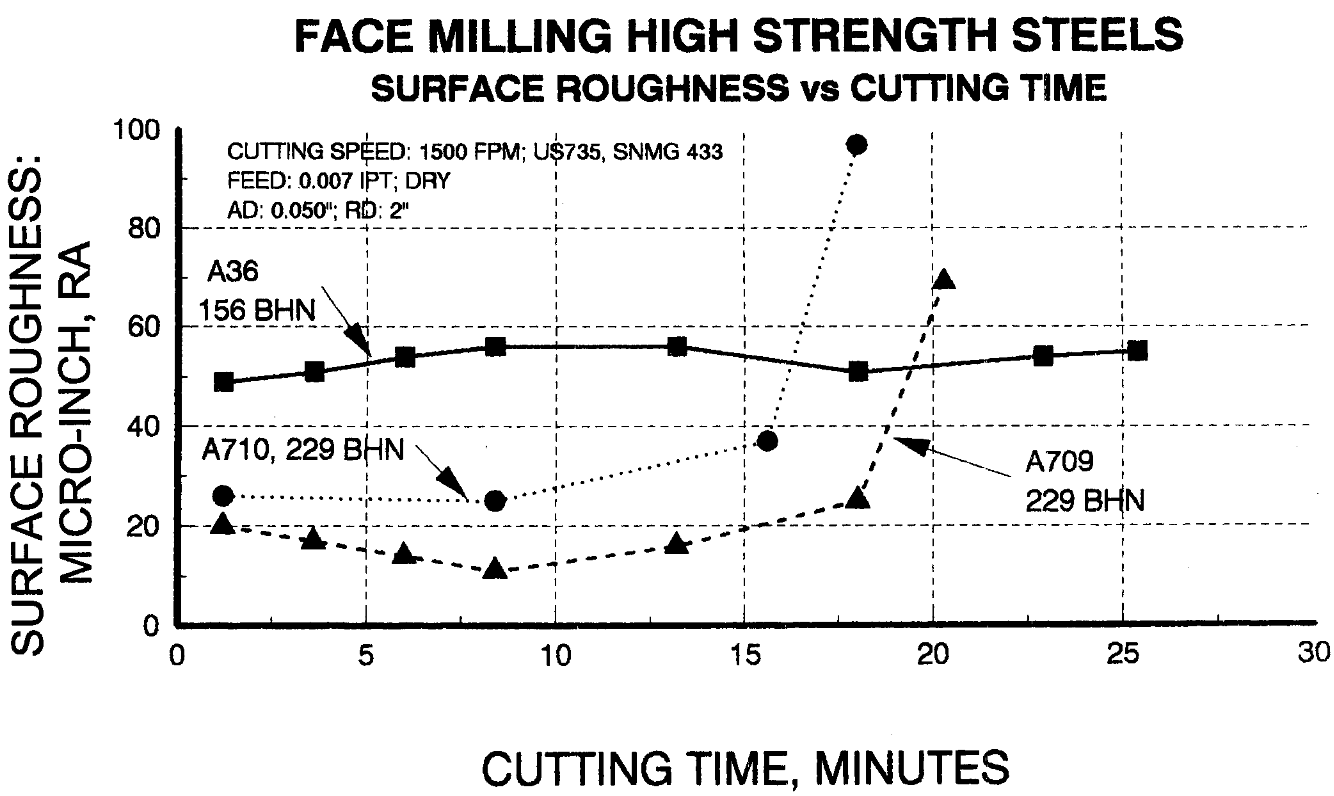


*Figure 21.* The change in surface roughness as a function of cutting time for the three steels. The surface roughness for A36 stayed relatively constant between 50-57 µin up to 25 minutes when cut at a rate of 1500 fpm and a feed rate of 0.007 ipt. In contrast, although the A710 and A709 steels had superior surface finishes that were 50% less rough than the A36, where surface roughness sharply increased after about 15-17 minutes of operation.

The overall conclusions from these single-tooth face milling tests prove that careful selection of the machining parameters can provide excellent surface finishes on all three steels. Most surface grinding operations can be eliminated on any of these structural steels by careful selection of the milling parameters of tool material, insert nose radius, cutting speed, and feed rate.. Milling without a cutting fluid is acceptable practice. Tests with a cutting fluid should be performed before including it in a production operation.

### *C. End Milling*

Most of the end mills used in these tests were made of HSS. The specific grade of "regular" HSS is rarely given, but most manufacturers use grades M1, M2, and M10 somewhat interchangeably, depending on price and availability. In addition to the commonly used grades, a "premium" grade of HSS, alloy M42, containing 8% cobalt for higher hot-hardness, was used. A listing of compositions of common high speed steels can be found in *Text Table 2.*

The M series of HSS contains varying amounts of chromium, molybdenum, tungsten and vanadium. At elevated temperatures, which are sustained at the edges of the cutting edges of end mills, carbides of these alloying elements precipitate out of solid solution, thereby increasing hot hardness. M1 principally relies on tungsten, whereas M2, M3 and M4 rely on molybdenum, tungsten and vanadium. M30 up to M48 HSSs contain varying amounts of molybdenum, tungsten and vanadium, but also a substantial addition of cobalt, which can be as low as 4.5% in M30 and as high as 12.25% in M44.

HSS made by powder metallurgy (PM) methods have better and finer dispersions of carbides. These PM steels are often referred to as "micro-grain carbides" because they are substantially smaller in size than in the conventional furnace melted and wrought versions which have larger sized carbide particles.

#### *(1). End Mill Parameters*

The end milling tests were performed on the same machine as the face milling tests, the three-axis Tongil CNC Machining Center, equipped with a 20 hp spindle drive, and with the same work materials, including the A36 steel plate at 156 BHN, the A710 Grade B steel plate at 229 BHN and the A709 HPS 70W steel plate at 229 BHN.

A coated HSS type of end mill was tested. The gold colored exterior (multiple coatings are sometimes used) coating was designated as titanium nitride (TiN). The coating(s) are usually applied over standard grade M1, M2, or M10 high speed steels. Premium M grade HSSs can be used for applications on high temperature alloys (nickel, titanium, etc.) or ferrous alloys harder than 40-45 Rockwell C. Solid micro-grain carbide, ½ inch diameter, 4 flute end mills, with and without titanium nitride (TiN) coatings, were also evaluated for their effectiveness in machining the three structural steels.

The end mills were clamped in two standard "Cat 40" taper end mill holders, one for ½ inch and one for ¾ inch end mills. This is a standard spindle taper for CNC machining centers of this size. The cutters were clamped in the holders with one set screw, which engaged a precision, recessed flat, ground into the shank of each end mill.

The solid carbide end mills, which have no set screw flat, were gripped in a collet-type end mill holder. This holder grips the end mill around its entire perimeter, providing adjustable overhang of the end mill from the end of the holder. By minimizing the length of the overhang, the rigidity of the setup is increased.

Both 3 flute and 4 flute end mills were used in these tests. In most of the tests, 4 fluted were used. All the end mills were of normal length (not long or extra-long), with the shank and the cutting diameters the same size. Most of the end mills were made in the USA, but a few imported end mills were evaluated for cost effectiveness.

A water base cutting fluid, Master Chemical's Trim Sol, was diluted 1 part fluid to 20 parts tap water, and was used throughout the end milling tests. A generous flow of the fluid was applied to the end mill with two flexible nozzles. The work pieces were clamped in two 8 inch Kurt heavy duty milling vises, which were keyed and bolted to the table of the machining center for maximum rigidity.

The recommended cutting speed for end milling structural steels with HSS cutters is 100 fpm, and was used throughout the tests. The recommended feed rates were 0.002 ipt for ½ inch diameter end mills, and 0.004 ipt for the ¾ inch diameter end mills. The axial depth of cut was equal to the cutter diameter with both the ½ inch and ¾ inch diameter end mills. The radial depth of cut was equal to 1/4 of the cutter diameter for both sizes of end mills. All these parameters are recommended in the *Machining Data Handbook* and are considered normal, acceptable practice in production machining applications.

The solid carbide end mills were tested under the same feed, radial and axial depths of cut as the high speed steel end mills. The major advantage of carbide cutters over high speed steel is the higher cutting speed used with the carbide cutters. In this test the cutting speed was increased from 100 fpm for HSS up to 350 fpm for the carbide end mills, which is in keeping with recommendations from the *Machining Data Handbook.*

The tool geometry of the carbide end mills was very similar to the geometry of the HSS end mills. Both types of cutters had sharp corners at the ends of the flutes, the normal shape of the as-purchased end mills. This configuration provides the capability of milling a square corner onto the work piece.

All the test result data plotted in *Figures 22* through *61* are listed in Appendix *Data Table 3* through *Data Table 10.* Cutters, feed rate, radial and axial depths of cut, and cutting fluid used are all summarized in Appendix *Data Tables 3* through *10.* Down milling was used throughout this project. Appendix *Data Tables 3* through *7* contain results generated with ½ inch diameter end mills, and Appendix *Data Tables 8* through *10* contain results produced with ¾ inch diameter end mills. Generally, the order of the three steels evaluated was A36 first, A709 second, and A710 third, with only a few exceptions.

The surface roughness $R_A$, commonly called surface finish, was measured and recorded after the first pass and then every other pass for each new test. Tool wear was also measured along with the surface roughness. Cubic inches removed by milling, although not listed in the Tables, is easily calculated by the following equation:

$$Q = L \times R_D \times A_D$$

where:

Q is total metal removed, $in^3$

L is the total length of cutter travel, the number of passes x 12 inches/pass

$R_D$ is the radial depth of cut equal to 1/4 of the cutter diameter

$A_D$ is the axial depth of cut, equal to the cutter diameter

The total cutting time is calculated by dividing L, the total travel by the table feed, in ipm. The quantity ipm is determined by:

$$[\text{ipm}] = [\text{ipt}] \times [\text{number of flutes}] \times [\text{rpm}]$$

The number of revolutions per minute rpm is given by the CNC controller, while the feed rate, ipt and the number of flutes are selected by the operator when the cutters are purchased.

*Figure 22 through Figure 41* have results with ½ inch diameter end mills exclusively. *Figures 42, 43, and 44* compare the results of diameter cutters with the results of ¾ inch diameter cutters on all three steels. *Figure 45 through Figure 61* show results with ¾ inch diameter end mills exclusively.

*(2). Surface Roughness*

*Figure 22 through Figure 31* use surface roughness as the basis of comparison for the variables explored. The primary influence on surface roughness is the peripheral edge wear on the cutter. However, rigidity can also have an influence, particularly when the edge wear increases. The operation of peripheral end milling always leaves a shoulder or rib on the work piece. As the rib gets progressively thinner with succeeding passes, the rigidity decreases. When the rib gets very thin and the cutter wear is relatively high, the roughness readings are higher. This occurrence accounts for most of the otherwise unexplainable spikes in roughness readings. Whenever unusual readings were obtained, second readings were taken to verify or correct the first reading.

*Figure 22* shows the effect of cutting time on surface roughness for the three steels, using a ½ inch diameter M2 HSS end mill. The A36 steel produced the highest or roughest readings while it generated tool wear more quickly than the other two steels. There was little difference between the roughness readings of the A709 and the A710 steels.

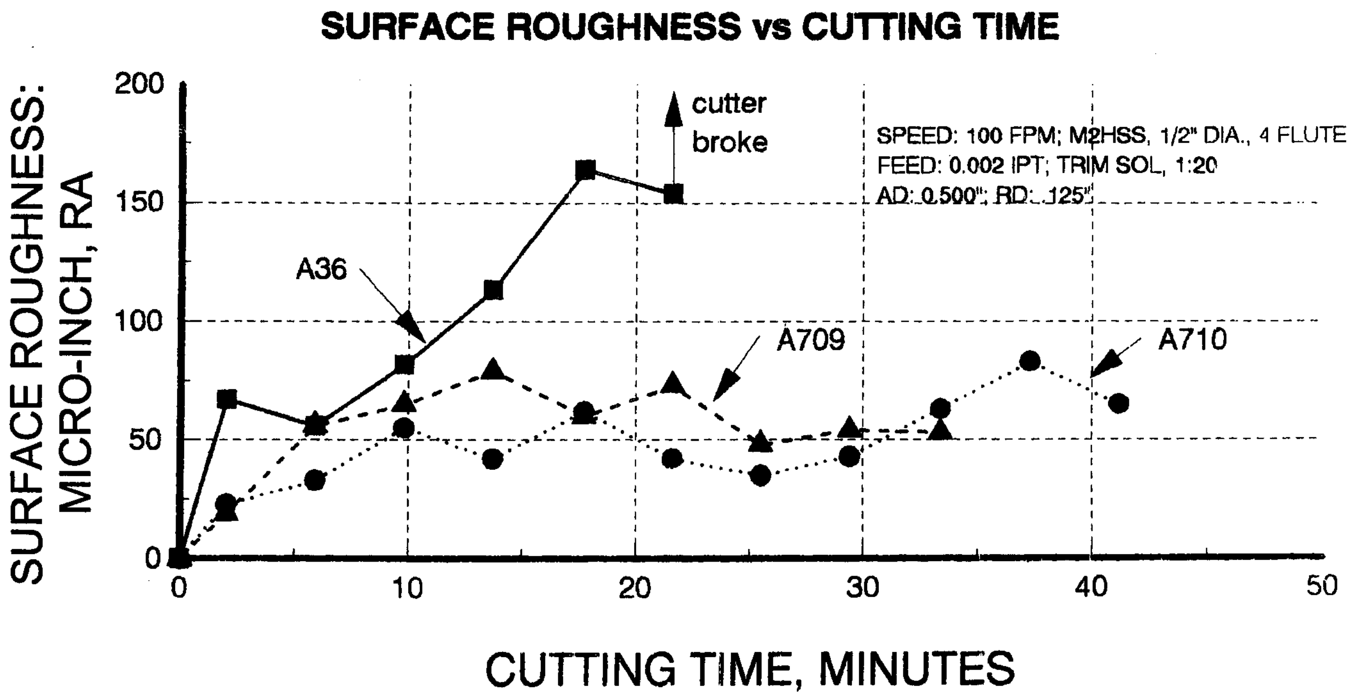


*Figure 22.* The comparison of surface roughness shown as a function of cutting time with an M2 high speed steel 4-flute end mill cutter with cutting fluid at 100 fpm. The two HP steels have minor differences in surface finish in the general range of 50 ± 20 µin, whereas the A36 steel surface shows a linear rise of progressively increasing roughness to about 150 µin, after which the cutter broke. M2 tool steel is a high carbon alloy with 6% tungsten, 5% molybdenum, 4% chromium and 2% vanadium.

The three steels are again compared in *Figure 23* using an M42 HSS end mill, which is more wear resistant than the M2 high speed steel cutter. Most of the readings were under 100 µin with many under 75 µin. *Figure 23* is a plot similar to *Figure 22*, using M42 high speed steel at the same parameters. M42 high speed tool steel has slightly higher carbon content than M2, and is alloyed with 9.5% molybdenum, 8% cobalt, 6% tungsten, 3.75% chromium, 1.5% tungsten, and 1.15% vanadium. M42 is hardenable to 67-70 Rockwell C.

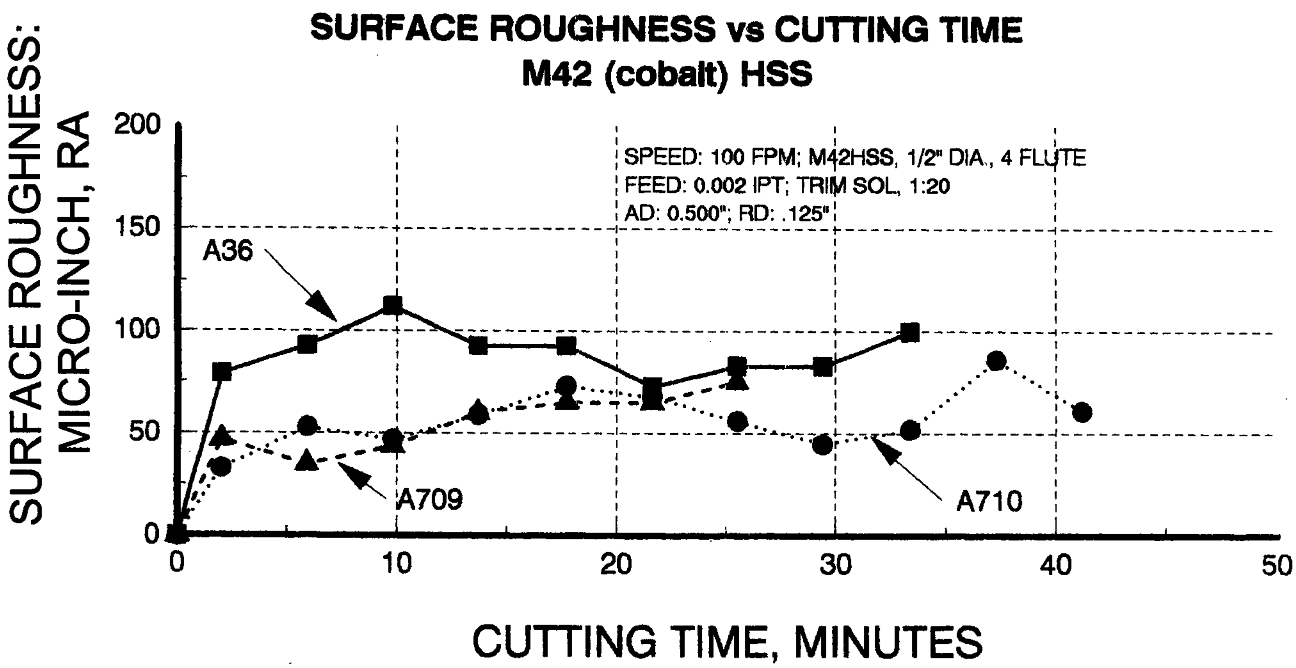


*Figure 23.* The comparison of the surface roughness of the three steels is shown using an M42 high speed steel 4-flute end mill operating at 100 fpm with a cutting fluid. The HP steels have a finish of 50 ± 20 µin comparable to that obtained with M2 high speed steel. However, the surface finish of the A36 was substantially improved by use of this cutter, providing a comparable finish of about 75-100 µin. M42 high speed tool steel has slightly higher carbon content than M2, and is alloyed with 9.5% molybdenum, 8% cobalt, 6% tungsten, 3.75% chromium, 1.5% tungsten, and 1.15% vanadium. M42 is hardenable to 67-70 Rockwell C.

*Figure 24* shows the three steels milled with titanium nitride-coated cutters. The A710 steel consistently provided the lowest roughness readings and the smoothest finish, while the A36 steel had the roughest finish. The three steels are compared using 3 flute end mills instead of 4 flute cutters as in the previous tests in *Figure 25.* The cutting time is noticeably shorter with 3 flute end mills.

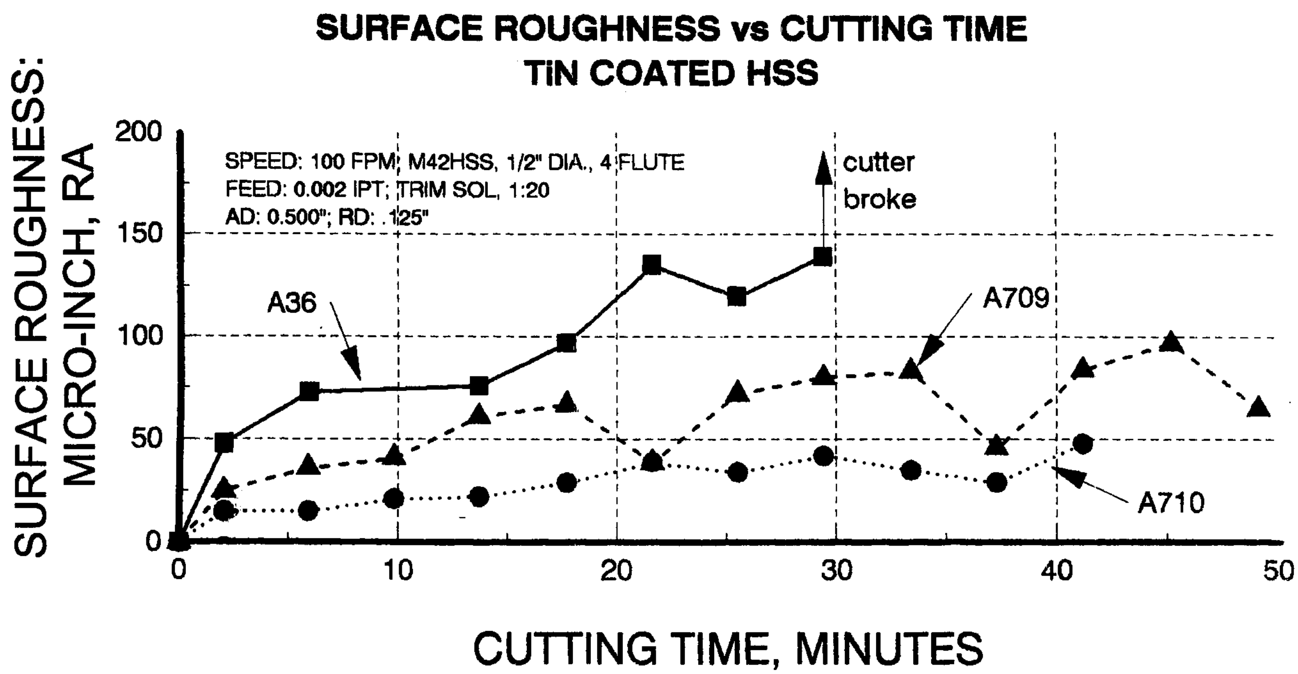


*Figure 24.* The comparison of the three steels using an M42 end mill with 4 flutes, except that the cutter was coated with titanium nitride. As in the previous tests using high speed steels M2 and M42, the two HP steels had surface roughness values that were in the general vicinity of 50 µin. Several of the initial readings for the A710 were less than 25 µin. In contrast, the A36 steel had surface roughness values of 75 µin or more, with end mill break-up after 30 minutes of cutting time.

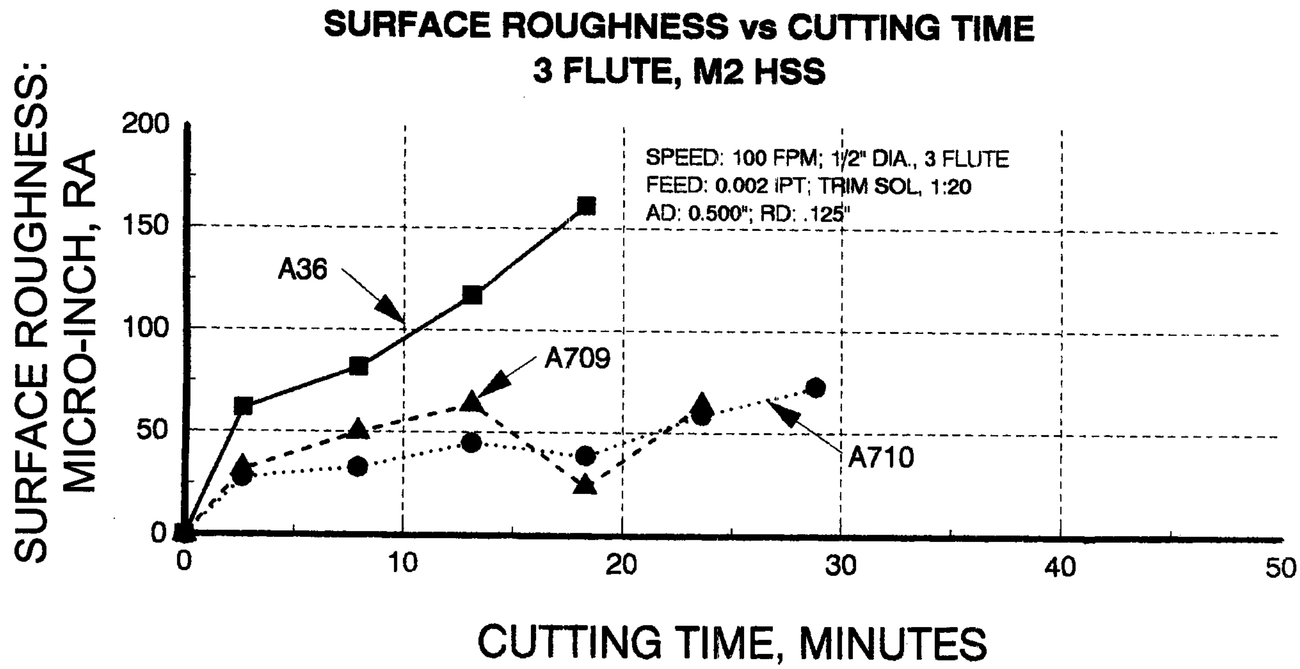


*Figure 25.* The comparison of the three steels using a 3-flute end mill of M2 high speed steel instead of a 4-flute mill. As in the previous tests, the HP steels maintain their average surface roughness of 50 µin up to 30 minutes, but the A36 steel surface linearly ramps up from 50 µin at 2 minutes to slightly more than 150 µin after only 15 minutes.

*Figure 26* shows the different types of tool material end milling the A36 steel. The M42 HSS end mill cut longer than the M2 or the TiN coated cutters, which broke to end those tests. *Figure 27* shows the three tool materials cutting A709 steel. While the three types of tool materials produced similar roughness readings, the TiN coated end mill cut about 25% longer than the others. *Figure 28* shows the three tool materials cutting A710 steel. There is surprisingly little difference in the roughness readings among the three tool materials, which also lasted the same length of cutting time.

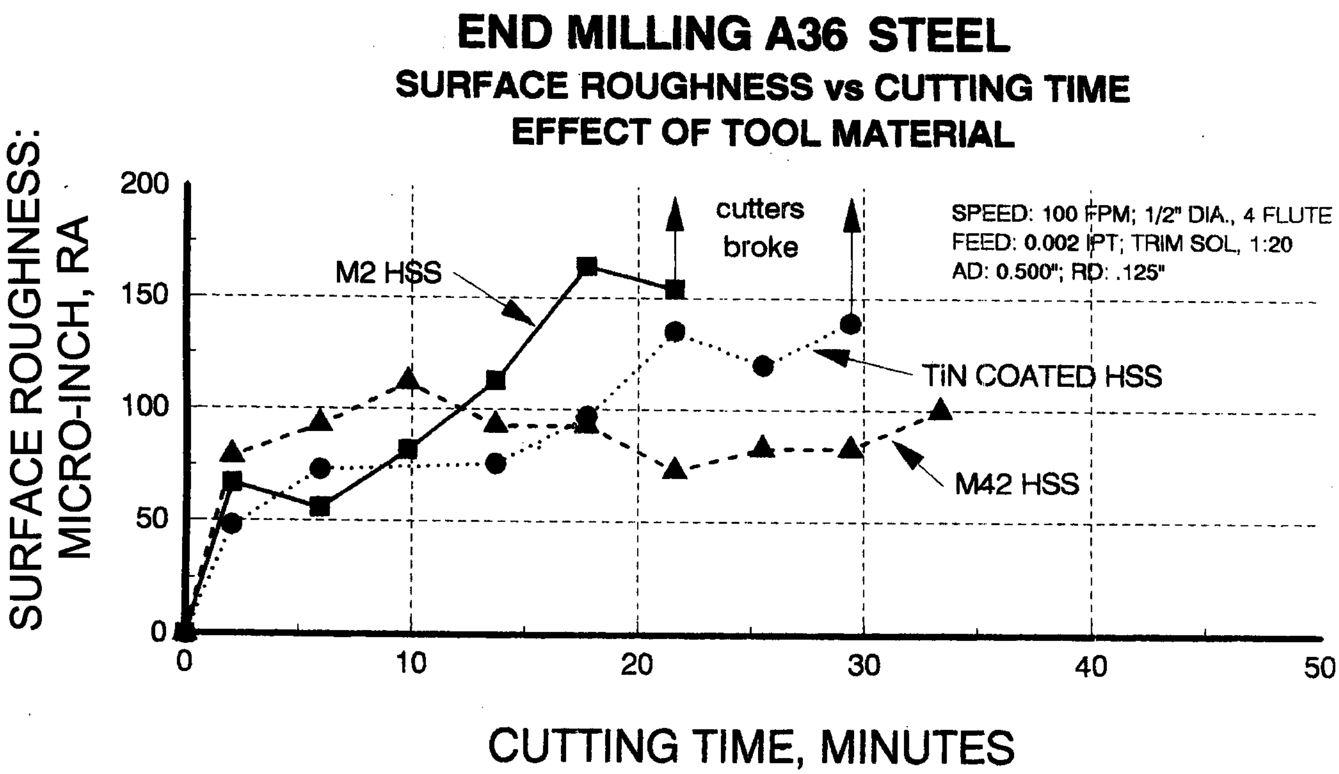


*Figure 26.* A comparison of different end mill tool steels when cutting A36 structural steel. After 12 minutes of cutting, the M2 steel sharply increased surface roughness, and eventually broke after 22 minutes of operation. There was a delay in the rupture of the same M2 high speed steel end mill coated with titanium nitride of about 18 minutes of operation, whereas the M42 end mill continued to operate, providing a surface of about 100 μin.

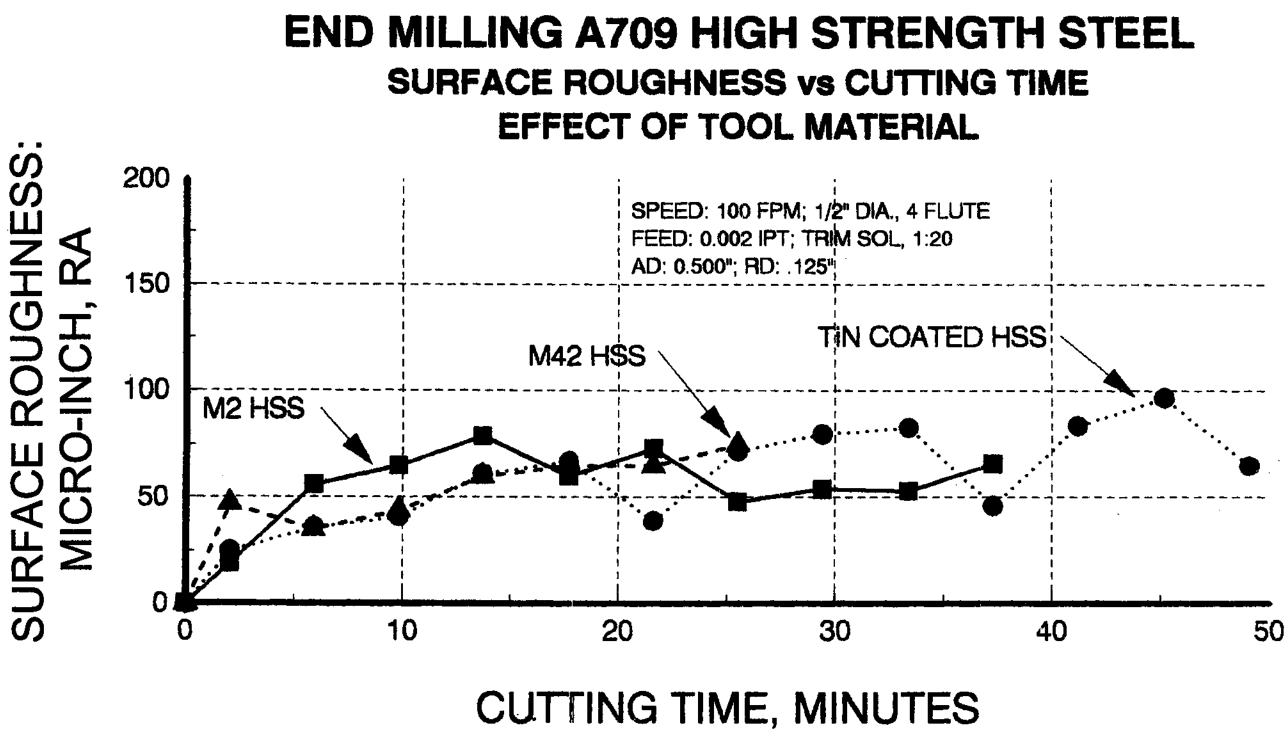


*Figure 27.* A comparison of different end mill tool steels when cutting A709 HP structural steel. After 25 minutes of cutting, the M42 end-mill eventually broke after 25 minutes of operation. There was a delay in the rupture of the M42 tool steel end mill of about 27 minutes of operation, whereas the M2 end mill coated with titanium nitride continued to operate, providing a surface finish of 100 μin or less.

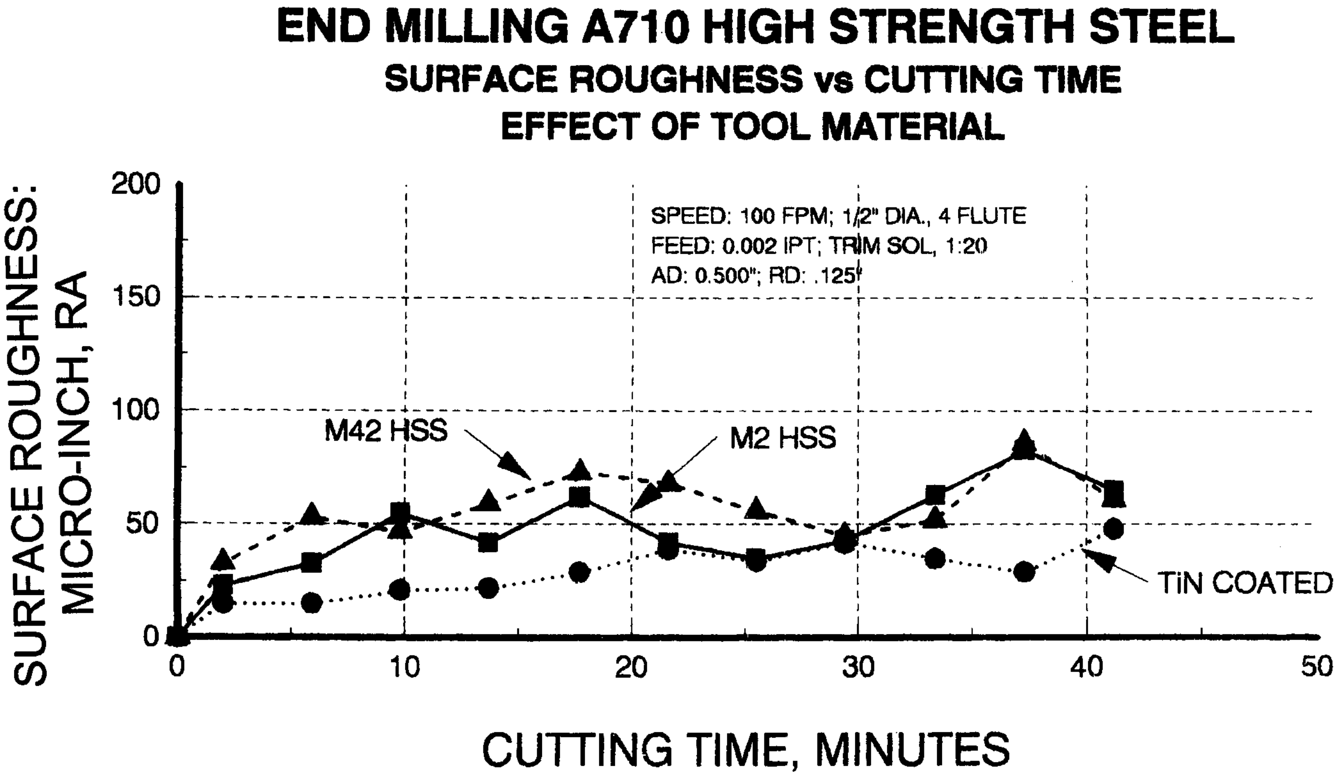


*Figure 28.* A comparison of different end mill tool steels when cutting A710 structural steel. After 42 minutes of cutting, the M2 high speed steel, the M2 coated with titanium nitride, and the M42 high speed steel with cobalt continued to operate for more than 40 minutes. During the time of operation, the surfaces were generally comparable, with the best finishes obtained with the M2 coated with TiN. Typical roughness values were about 50 µin for the M42 and M2, whereas the TiN coating provided a superior surface finish of less than 25 µin that continued up to about 20 minutes of operation.

*Figure 29* compares the 3 flute end mill with the 4 flute cutter. There is practically no difference in roughness readings. The highest readings were above 150 micro-inch. *Figure 30* compares the 3 flute with the 4 flute end mill on A709 steel. The roughness readings were generally lower with the 3 flute end mill. The results of milling the A710 steel with the 3 flute and 4 flute cutters are shown in *Figure 31*. Both types of end mills produced about the same roughness readings at the end of their respective tests, where the wear readings would be about the same.

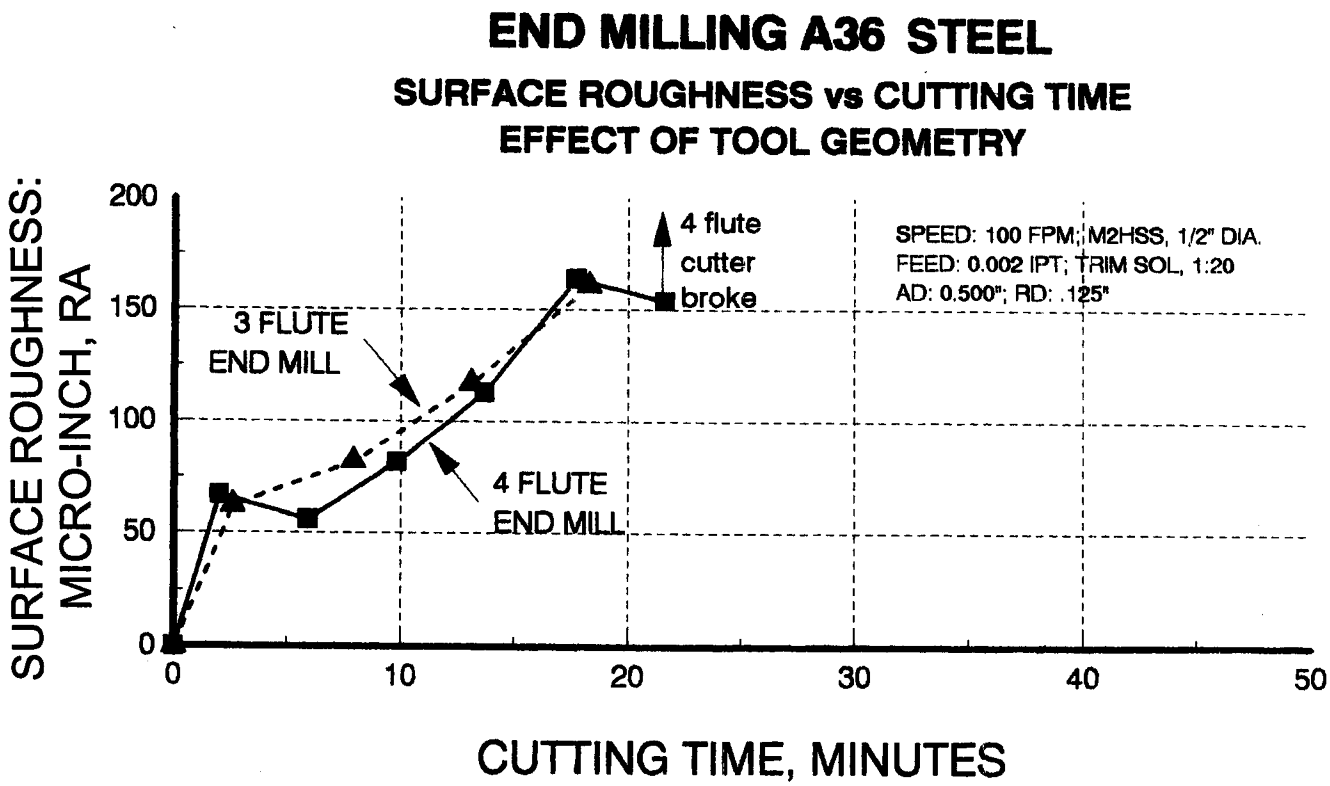


*Figure 29.* This plot compares the difference in performance between the 3-flute and 4-flute M2 high speed steel end mills when milling A36 steel. The surface roughness values are virtually parallel when considered as a function of cutting time.

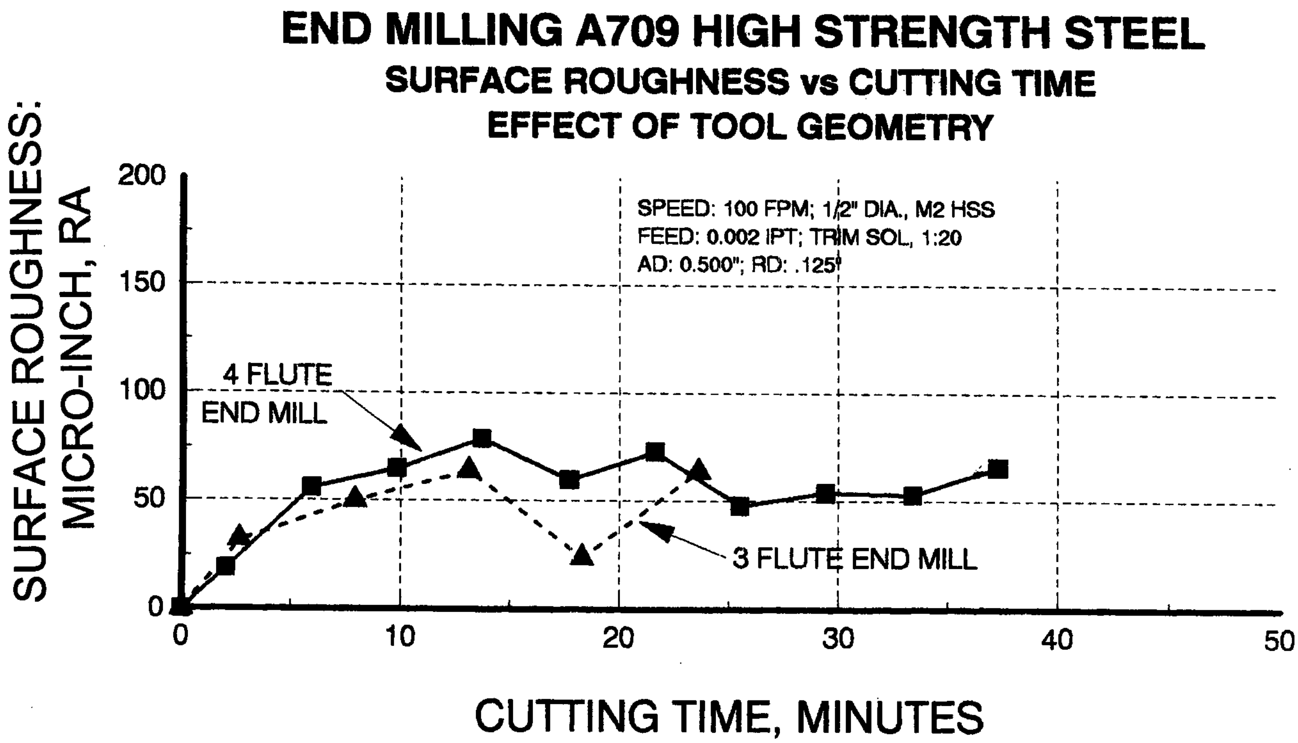


*Figure 30.* This plot compares the difference in performance between the 3-flute and 4-flute M2 high speed steel end mills when milling A709 HP steel. The surface roughness values are very comparable as a function of cutting time, except for a substantial decrease in roughness for the 3 flute mill after 13 minutes of operation. Cutting was halted due to flute wear.

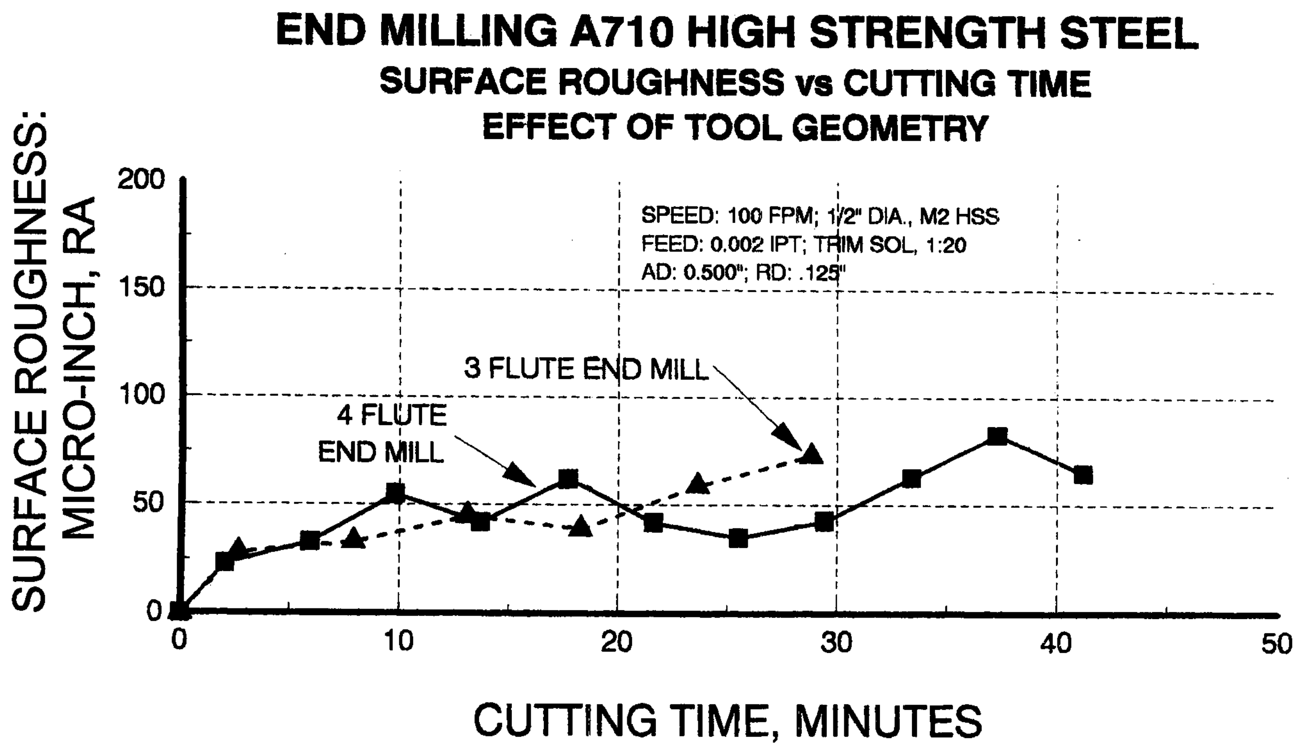


*Figure 31.* This plot compares the difference in performance between the 3-flute and 4-flute M2 high speed steel end mills when milling A710 HP steel. The surface roughness values are also very comparable as a function of cutting time as found in A709 HP steel, except for a slight increase in roughness for the 3 flute mill after 23 minutes of operation, where cutting was halted due to flute wear. For the 4-flute end mill, the surface roughness held in the vicinity of about 50 µin for about 30 minutes, then began to rise to a range of about 60-75 µin.

*(3). Tool Wear*

As previously mentioned, *Figure 32 through Figure 37* use tool wear (not surface roughness) as the basis of comparison for the three steels and the various end mills. *Figure 32* compares the three steels using an M2 HSS cutter. The A36 steel showed the poorest machinability, providing about half the tool life of the A709 and A710 steels.

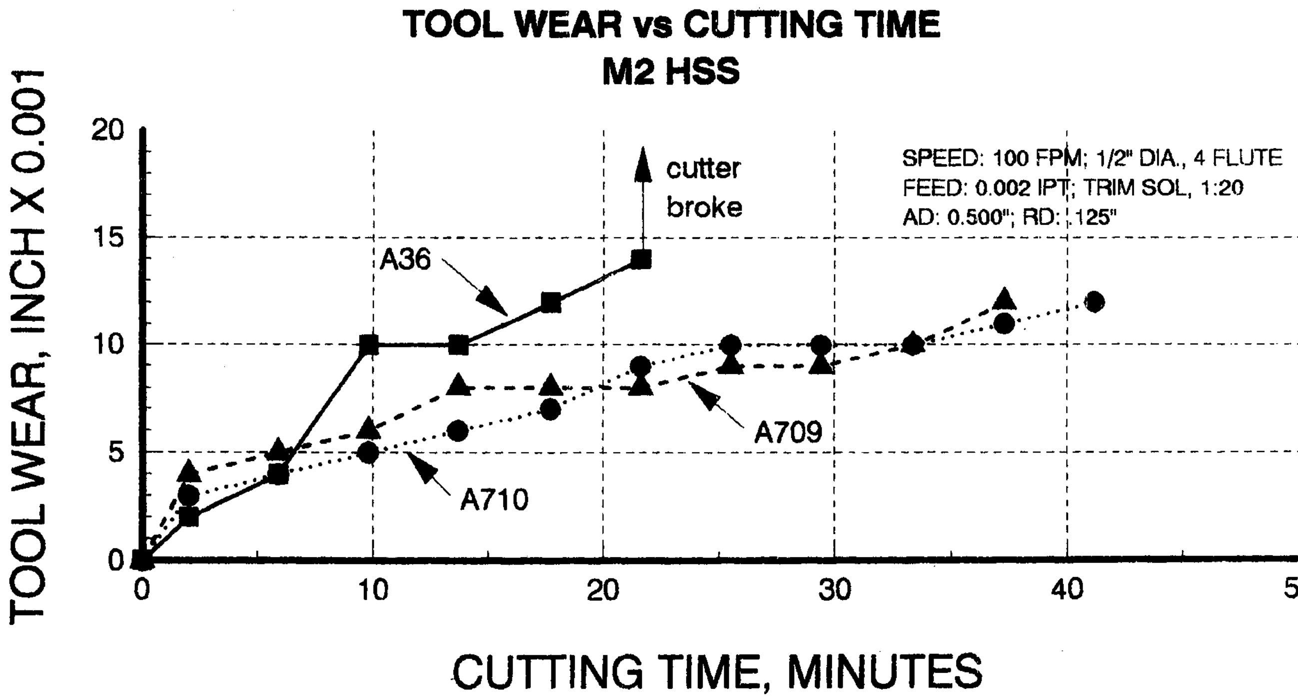


*Figure 32.* The comparison of the three steels of tool wear vs. cutting time using a 4-flute M2 high speed steel end mill with an oil-soluble cutting fluid. The two HP steels have virtually parallel performance, sustaining 0.012" of wear after about 40 minutes. In sharp contrast, the end mill machining the A36 steel broke in about 50% less time, whereby wear steadily increased after only five minutes of operation.

The three steels are again compared in *Figure 33,* using an M42 HSS cutter. In this example the A710 steel showed the best machinability, while the A709 steel had the poorest. The M42 HSS end mill broke with only 0.009 inch wear on the corners. The M42 HSS end mill, cutting the A36 steel, had two corners chipped, but not broken off, still able to cut the steel. The M42 HSS end mill produced the longest tool life of any cutter on the A36 steel.

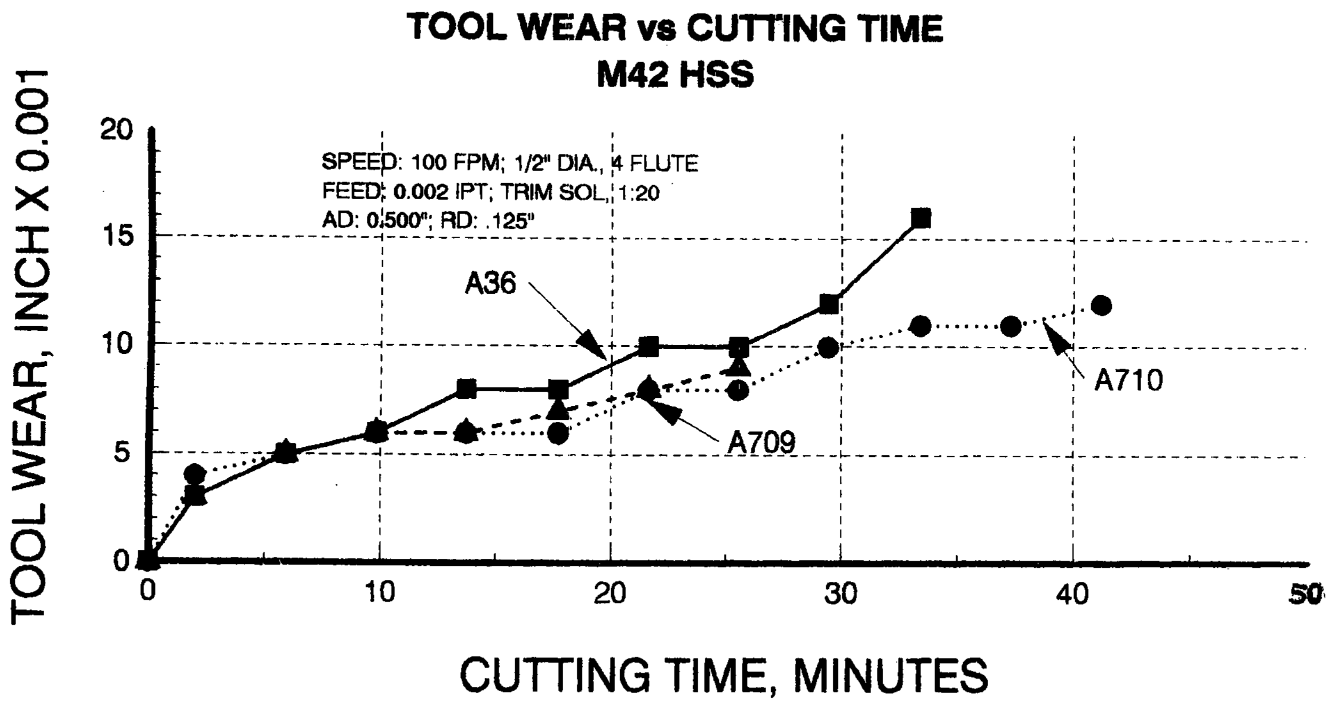


*Figure 33.* The comparison of the three steels of tool wear vs. cutting time using a 4-flute M42 high speed steel end mill with an oil-soluble cutting fluid. The two HP steels continue to have virtually parallel performance, sustaining 0.012" of wear after about 40 minutes. The A36 steel has wear equivalent to the HP steels up to 25 minutes, but began to sustain considerably more abrasion afterwards until the test was terminated after 34 minutes at 0.016" of wear.

Comparing the three steels using the TiN coated end mill is shown in *Figure 34.* This cutter produced the longest tool life on the A709 and A710 steels. The cutter with the A36 steel broke at 29 minutes.

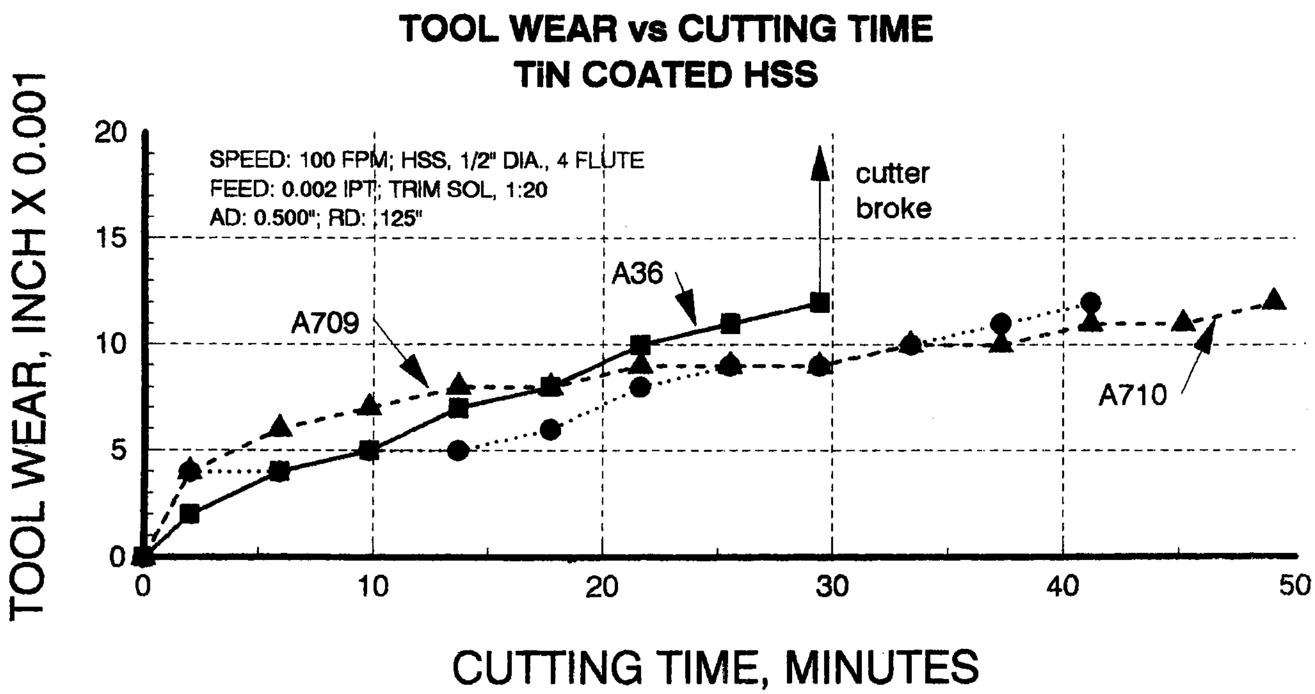


*Figure 34.* The comparison of the three steels of tool wear vs. cutting time using a 4-flute M2 high speed steel end mill coated with titanium nitride using an oil-soluble cutting fluid. All three steels have virtually parallel performance, sustaining 0.010" of wear after about 20 minutes, after which the end mill machining the A36 steel broke about 10 minutes later. The end mill machining the A36 steel broke in about 50% less time than the HP steels did after they reached 0.012" of wear.

*Figures 35, 36, and 37* compare the performance of a 3 flute end mill with the performance of a 4 flute end mill on the three steels. The A36 steel in *Figure 35* showed the least difference in tool life between the 3 and 4 flute end mills. The 4 flute cutter produced about 66% longer tool life.

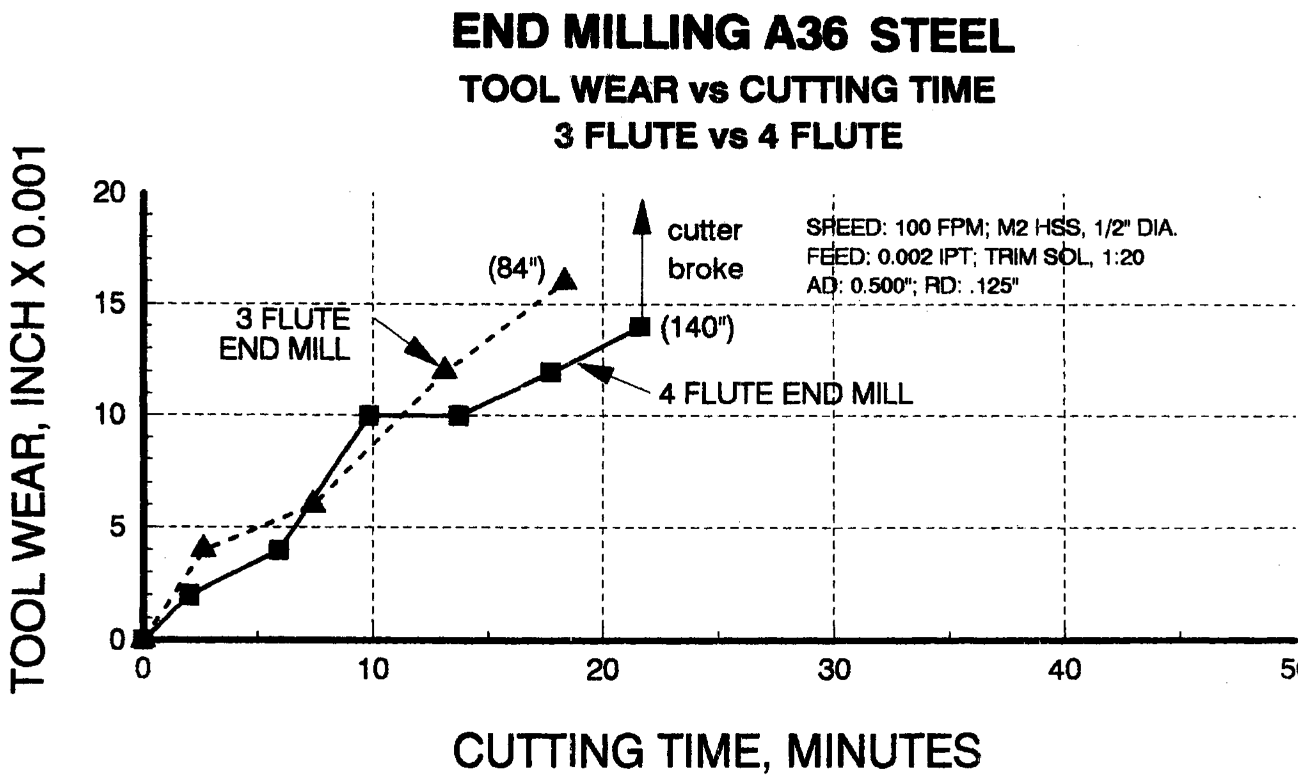


*Figure 35.* The comparison of A36 steel of tool wear vs. cutting time is shown using either a 3 or 4-flute M2 high speed steel end mill with an oil-soluble cutting fluid. This graph shows the difficulty of machining the A36 steel, with the 4-flute end mill only providing a limited (22%) life improvement over a 3-flute end mill. After only 20 minutes of operation, the 4-flute end mill suffered breakage.

*Figure 36* shows that the 4 flute end mill provided twice the tool life of the 3 flute cutter on the A709 steel. The 4 flute end mill almost doubled the tool life of the 3 flute cutter on the A710 steel in *Figure 37.*

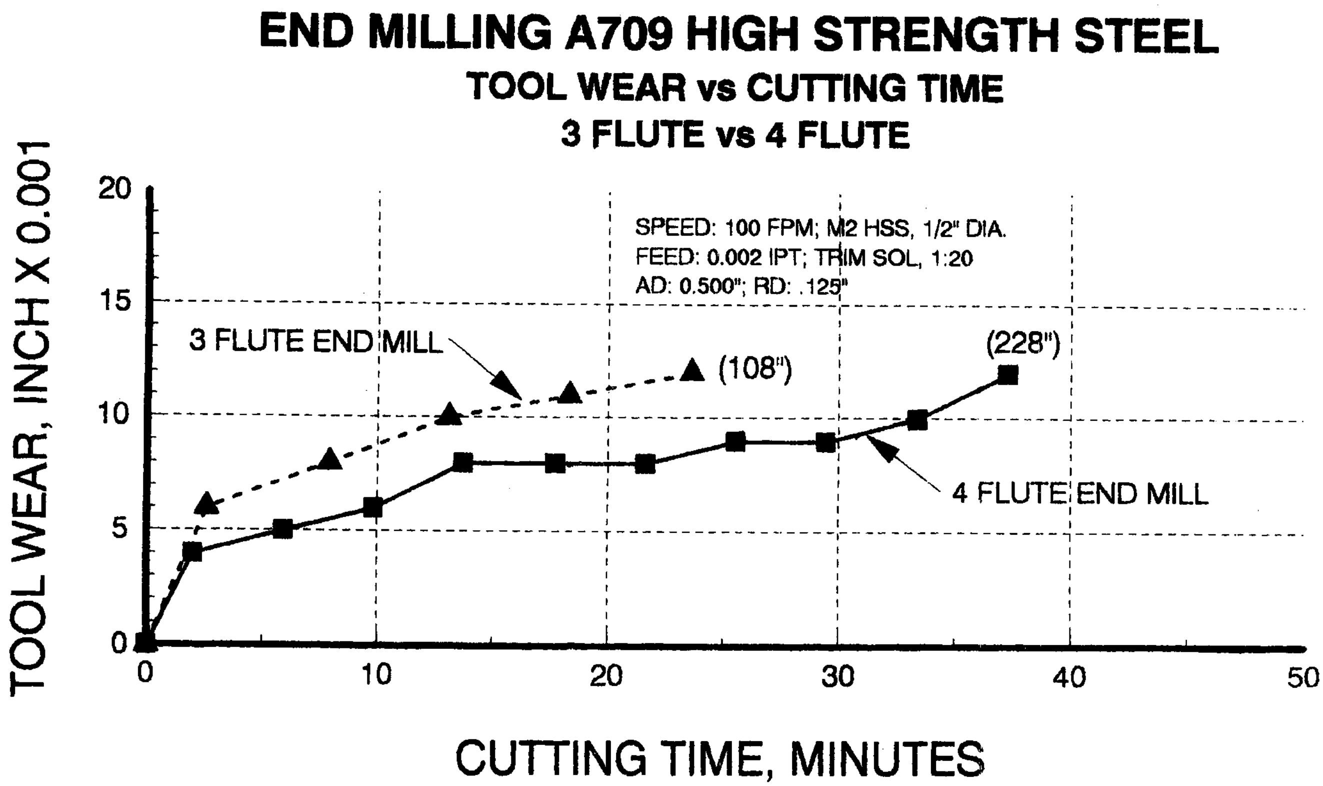


*Figure 36.* The comparison of tool wear vs. cutting time using 3 and 4-flute M2 high speed steel end mills with an oil-soluble cutting fluid for A709 HP 70W steel. The 4-flute end had clear superiority, taking 54% longer to sustain 0.012" of wear than the 3-flute end mill.

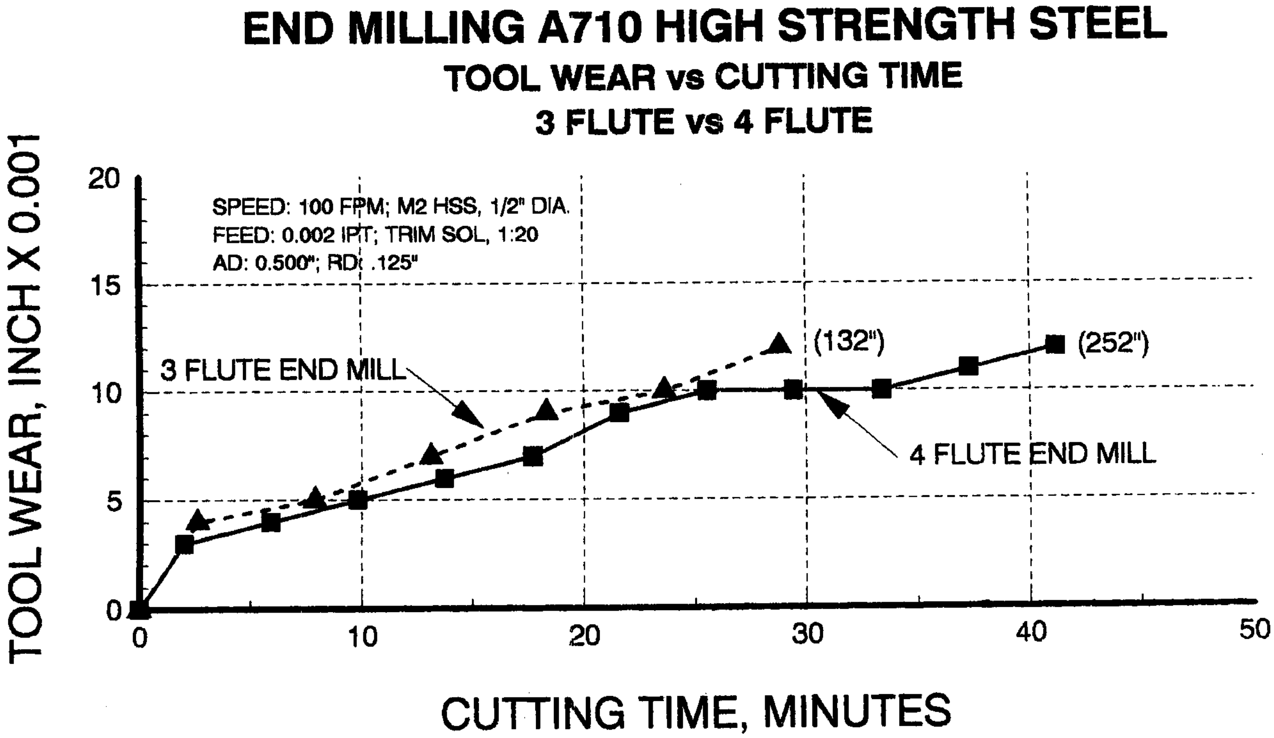


*Figure 37.* The comparison of tool wear vs. cutting time using 3 and 4-flute M2 high speed steel end mills with an oil-soluble cutting fluid for A710 Grade B steel. The two end mills had virtually identical performance up to 25 minutes, whereby the 3-flute end continued to linearly increase, whereas the 4-flute end mill had hit a plateau for another ten minutes. Afterwards, the same linear wear pattern experienced by both mills established itself after 33 minutes. In general, these two end mills had essentially very similar wear characteristics for the A710 steel.

A comparison of imported M2 and M42 HSS end mills with domestic cutters is shown in *Figure 38 through Figure 41* on A36 steel. The purpose of these tests is cost driven. If there is no mandate or incentive to purchase only domestically produced tooling, then imported cutters may prove to be cost-effective. The obvious trade-off could be in performance. If the performance of the imported end mill is close to the domestic product, then the purchase of imported cutters could prove to be cost-effective.

The imported M2 HSS end mill provided lower roughness readings than the domestic end mill in *Figure 38.* The comparison is repeated in *Figure 39* using M42 HSS end mill. The domestic cutter provided lower roughness readings than the imported end mill in this example.

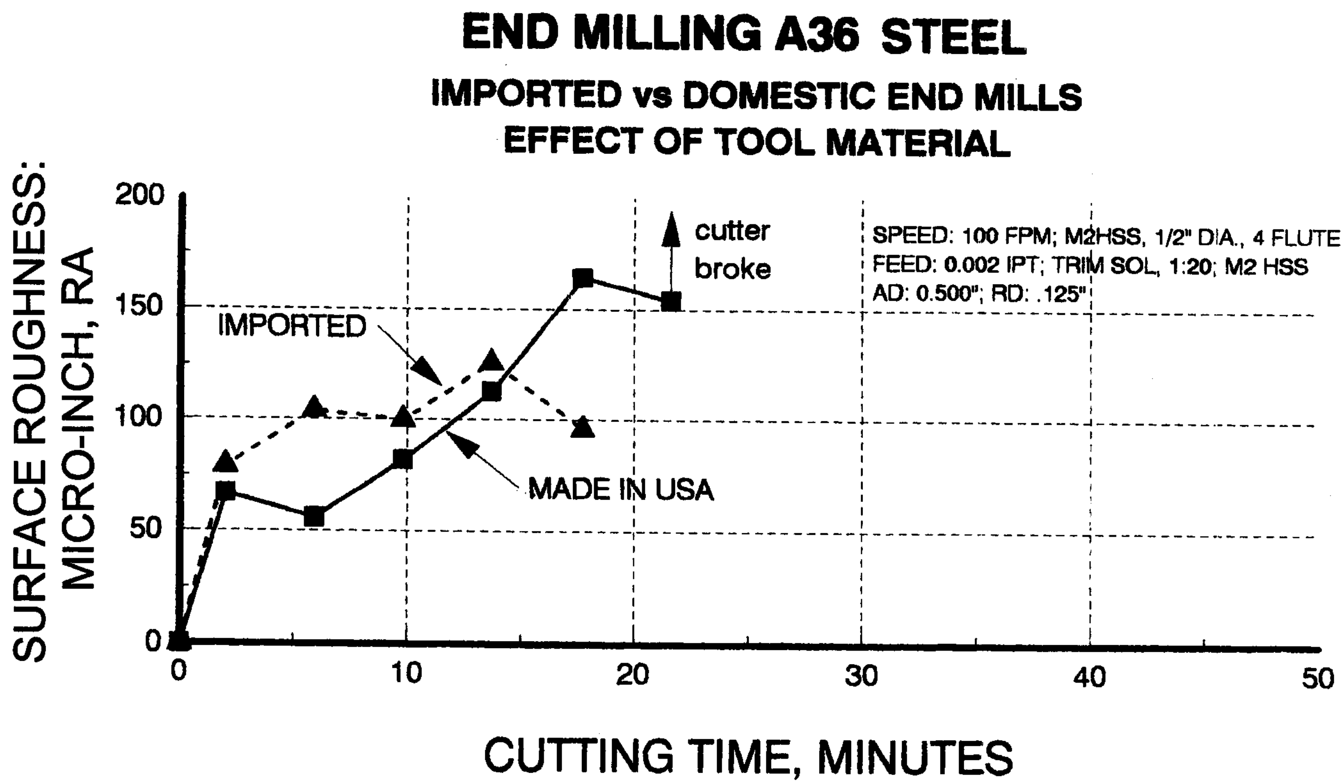


*Figure 38.* The comparison of surface roughness vs. cutting time is shown for domestic vs. imported end mills when machining A36 steel. Both 4-flute end mills were made of M2 high speed steel using a water-soluble oil cutting fluid. The surface roughness for domestic mills was superior up to about 15 minutes of operation, after which the domestic mill sustained wear, creating a rougher surface. Country of origin of the imported mill was not identified.

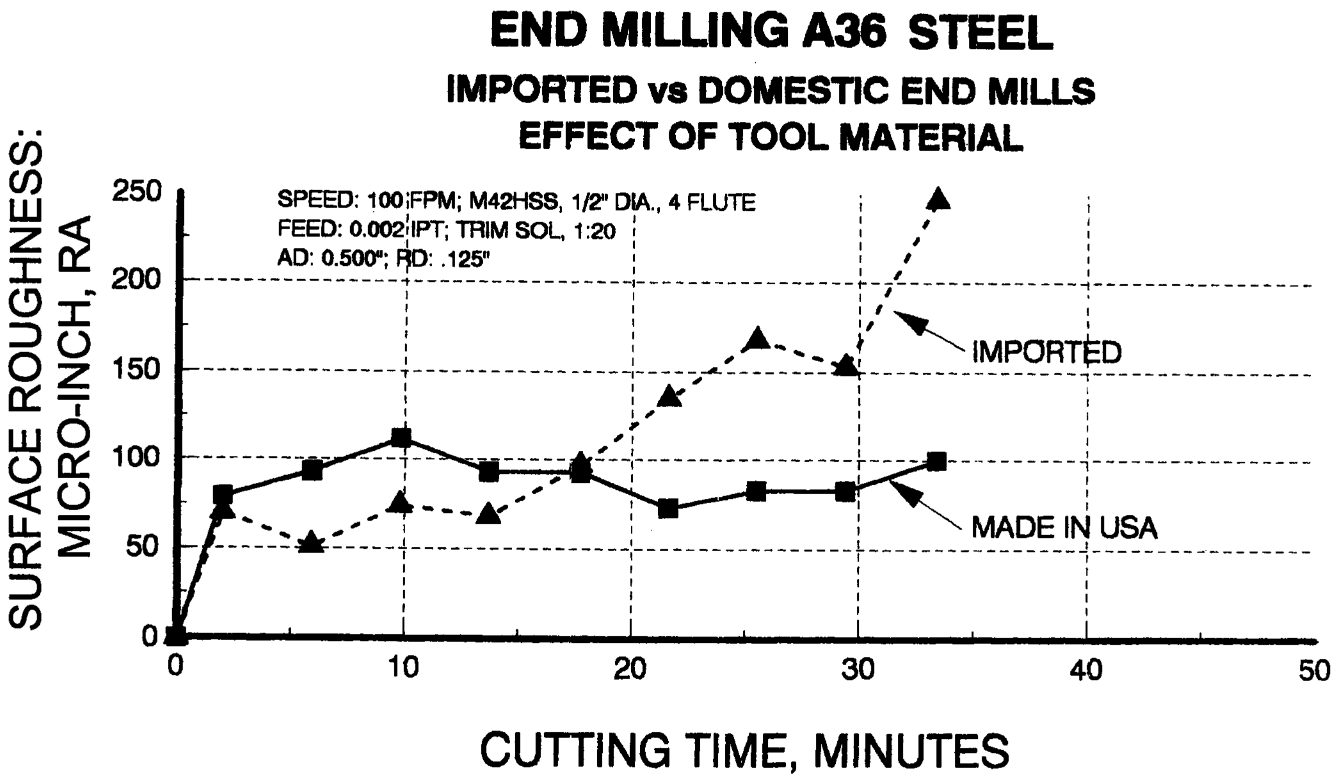


*Figure 39.* The comparison of surface roughness vs. cutting time is shown for domestic vs. imported end mills when machining A36 steel. Both 4-flute end mills were made of M42 high speed steel, using a water-soluble oil cutting fluid. The surface roughness for domestic mills was continuous at a range of 75-100 µin for up to 34 minutes, whereas the imported end mill sustained a significantly rougher surface after 18 minutes of operation. The sharp linear increase ultimately resulted in a very rough machined surface of 250 µin after 34 minutes of operation. Country of origin of the imported mill was not identified.

*Figure 40* shows that the domestic cutter provided about 30% longer tool life than the imported M2 HSS end mill in cutting, but had similar wear characteristics.

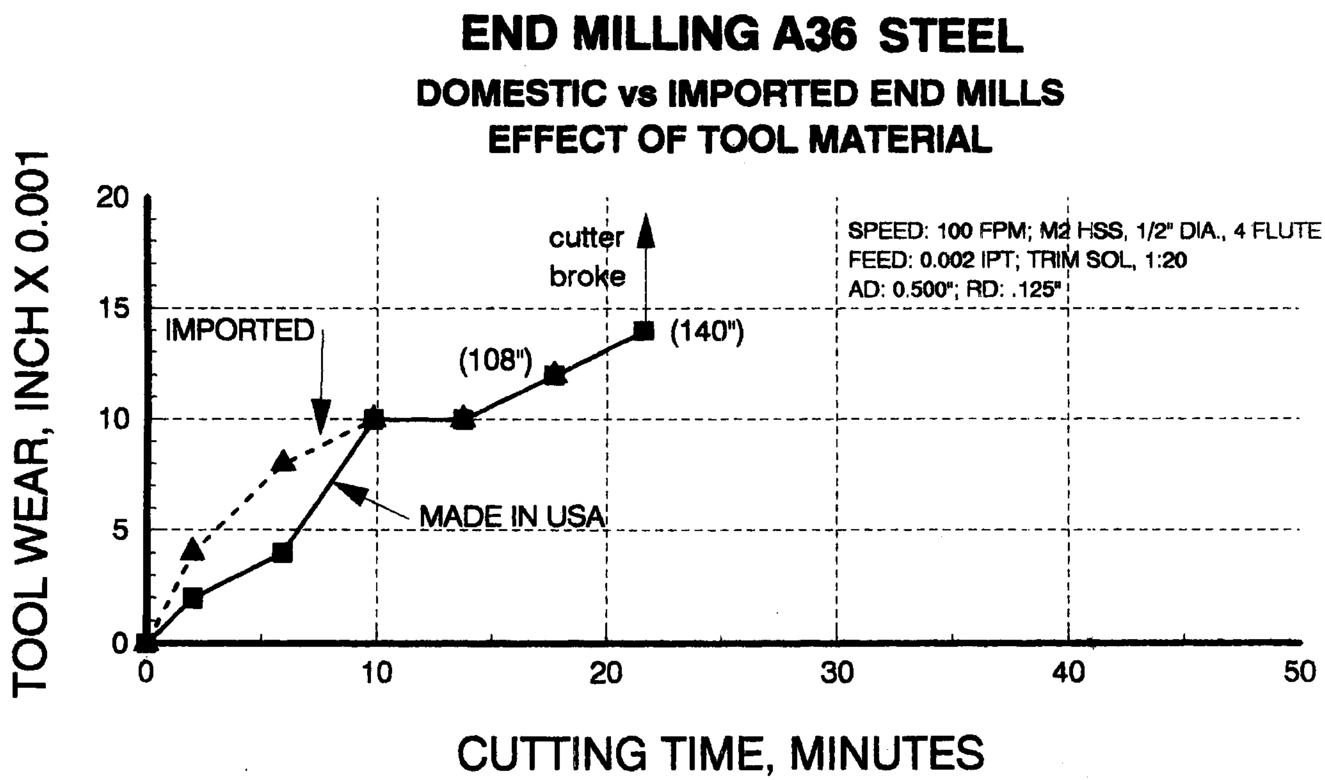


*Figure 40.* The comparison of tool wear vs. cutting time is shown for domestic vs. imported end mills when machining A36 steel. Both 4-flute end mills were made of M2 high speed steel, using the same water-soluble oil for cutting fluid. The tool wear for domestic mills was significantly less up to about 10 minutes of operation, after which both the domestic and imported end mills sustained similar wear. Country of origin of the imported end mill was not identified.

In *Figure 41*, the imported end mill had about 17% longer tool life for the same level of tool wear, 0.012 inch. The cost difference as of 2012 between imported M2 high speed steel end mills was about 10-40% of the domestic equivalent, and 20-45% for M42, depending on the end mill manufacturer. Prices will vary considerably among domestic manufacturers, and special sale prices are regular occurrences as well.

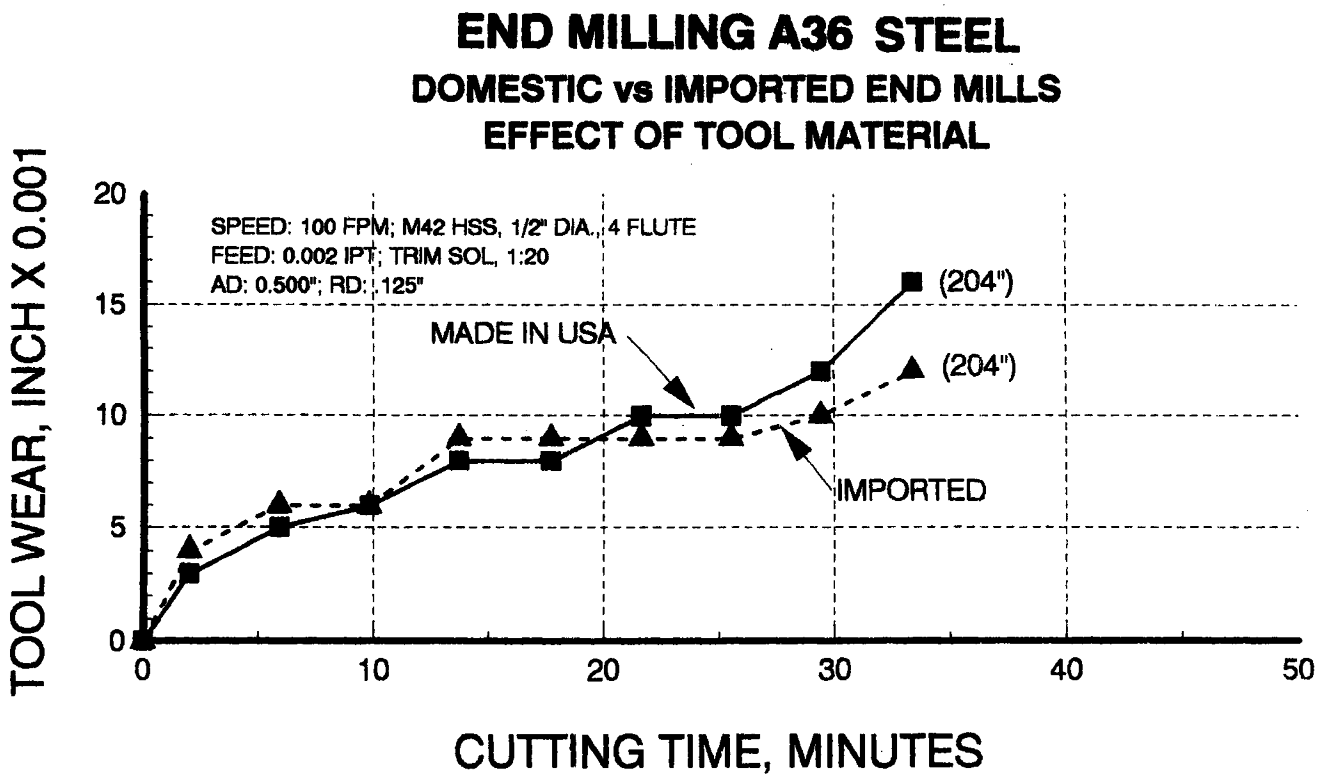


*Figure 41.* The comparison of tool wear vs. cutting time is shown for domestic vs. imported end mills when machining A36 steel. Both 4 flute end mills were made of M42 high speed steel, using the same water soluble oil cutting fluid. The tool wear for domestic and imported end mills was virtually equivalent as a function of cutting time. Country of origin of the imported end mill was not identified.

*Figures 42, 43, and 44* compare the performance of the 1/2" diameter cutter with the 3/4" M2 HSS end mill on the three steels. The A36 steel, shown in *Figure 42* has the poorest machinability of the three steels. In this example the more rigid 3/4" end mill produced lower roughness readings. In *Figures 43 and 44*, there was little difference in the roughness readings between the 1/2" and the 3/4" end mills on the A709 and A710 steels. *Figure 45* shows the surface roughness readings for all three steels with a 3/4" M2 HSS end mill. The highest readings were on the A36 steel, while the lowest readings were from the A709 steel.

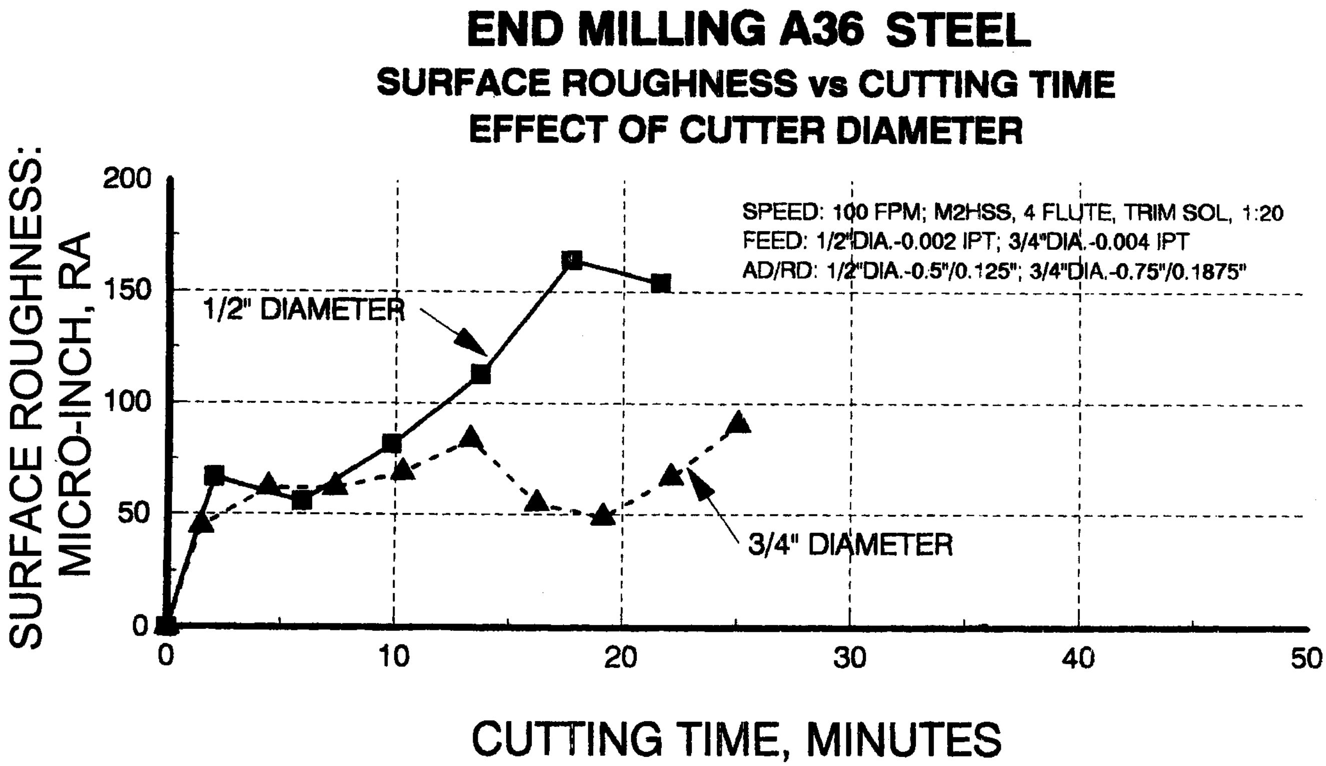


*Figure 42.* The comparison of surface roughness vs. cutting time for ½" and ¾" diameter 4-flute end mills made of M2 high speed steel using a cutting fluid when machining A36 steel. The surface roughness for ¾" diameter end mills was superior after 10 minutes of operation compared to ½" diameter mills by a substantial margin.

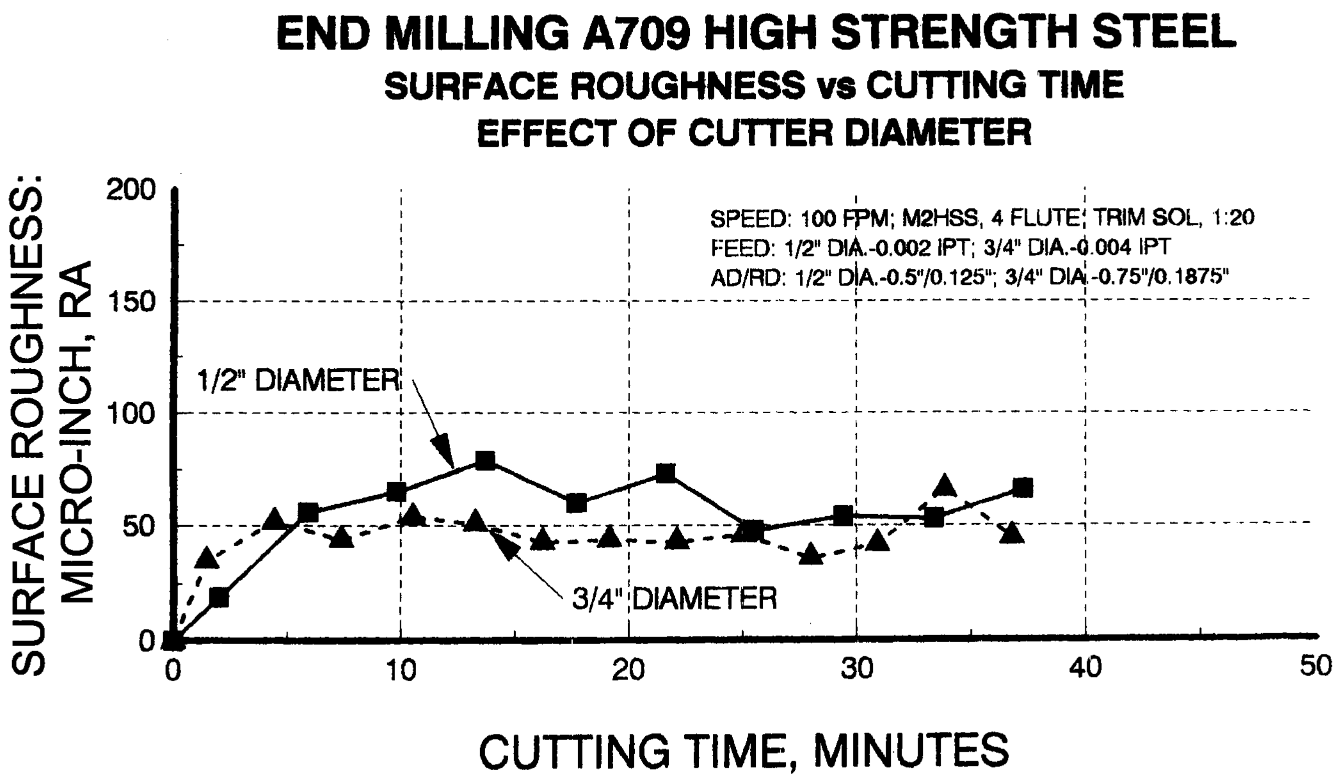


*Figure 43.* The comparison of surface roughness vs. cutting time for ½" and ¾" diameter 4-flute end mills made of M2 high speed steel using a cutting fluid when machining A709 HP 70W steel. The surface roughness for ¾" diameter end mills was largely parallel and equivalent to the performance of ½" diameter mills.

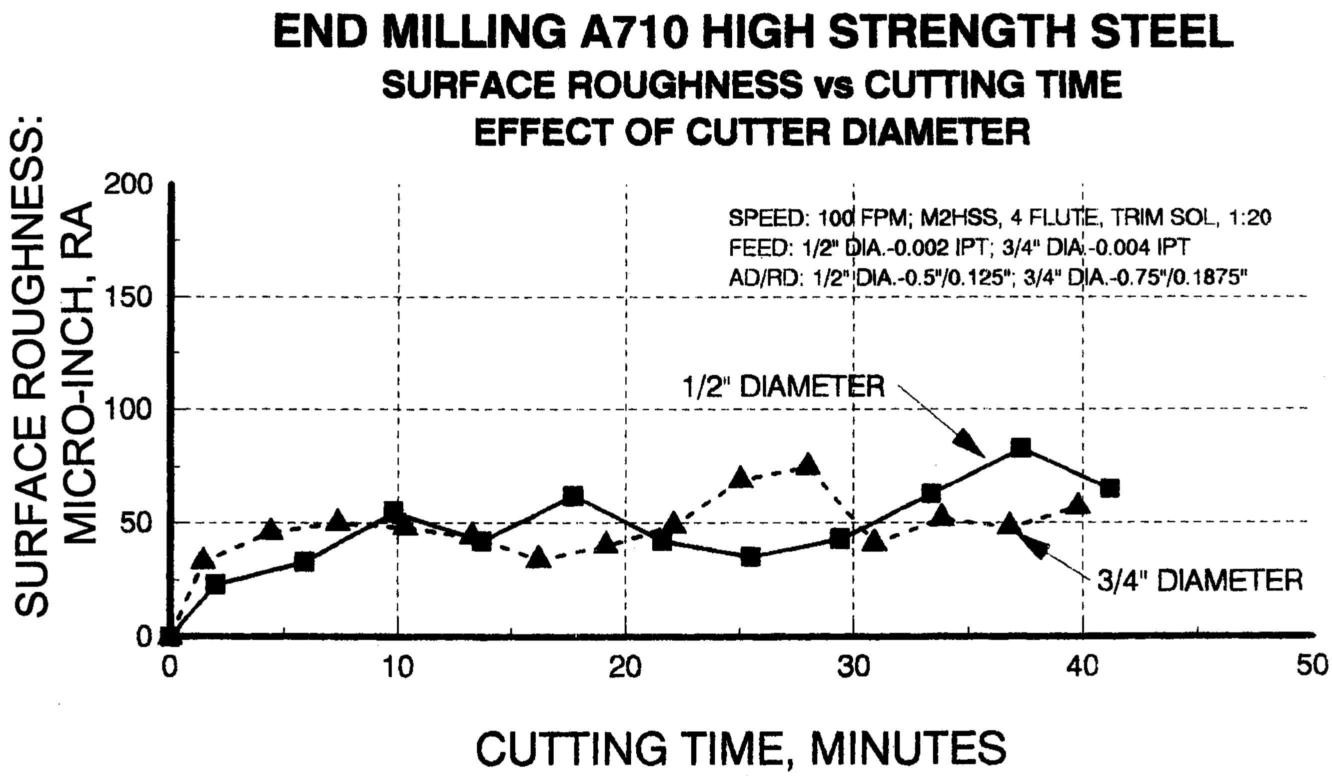


*Figure 44.* The comparison of surface roughness vs. cutting time for ½" and ¾" diameter 4-flute end mills made of M2 high speed steel using a cutting fluid when machining A710 Grade B steel. As shown in *Figure 43* for the A709 steel, the surface roughness for ¾" diameter end mills was parallel and virtually equivalent to the performance of ½" diameter mills.

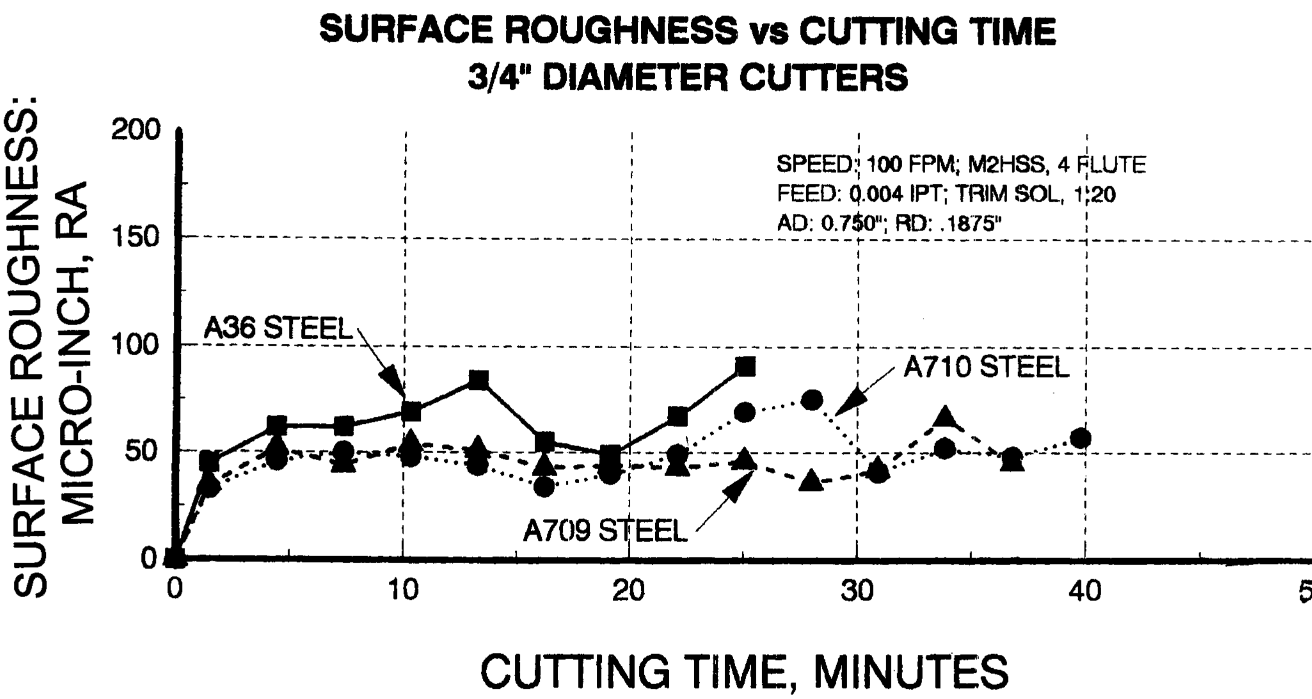


*Figure 45.* The comparison of all end milling all three steels on the basis of surface roughness vs. cutting time for ¾" diameter 4-flute end mills made of M2 high speed steel using a cutting fluid. As shown in previous figures, the surface roughness for ¾" diameter end mills was parallel and virtually equivalent to the performance of ½" diameter mills for both HP steels, but surface roughness was significantly greater for end milled A36.

Tool wear versus cutting time comparing ½ inch and ¾ inch diameter end mills on all three steels is shown in *Figures 46, 47, and 48.* The ¾ inch cutters, having greater beam strength, tolerated greater corner wear without breaking than the ½ inch diameter cutters. However, the cutting time was essentially the same with both size cutters on the A709 and the A710 steels, as shown in *Figures 47 and 48.* The ¾ inch end mill ran slightly longer on the A36 steel in *Figure 46.* The tool wear of the three steels is shown in *Figure 49.* The A709 steel had a slightly longer tool life than the A710 steel.

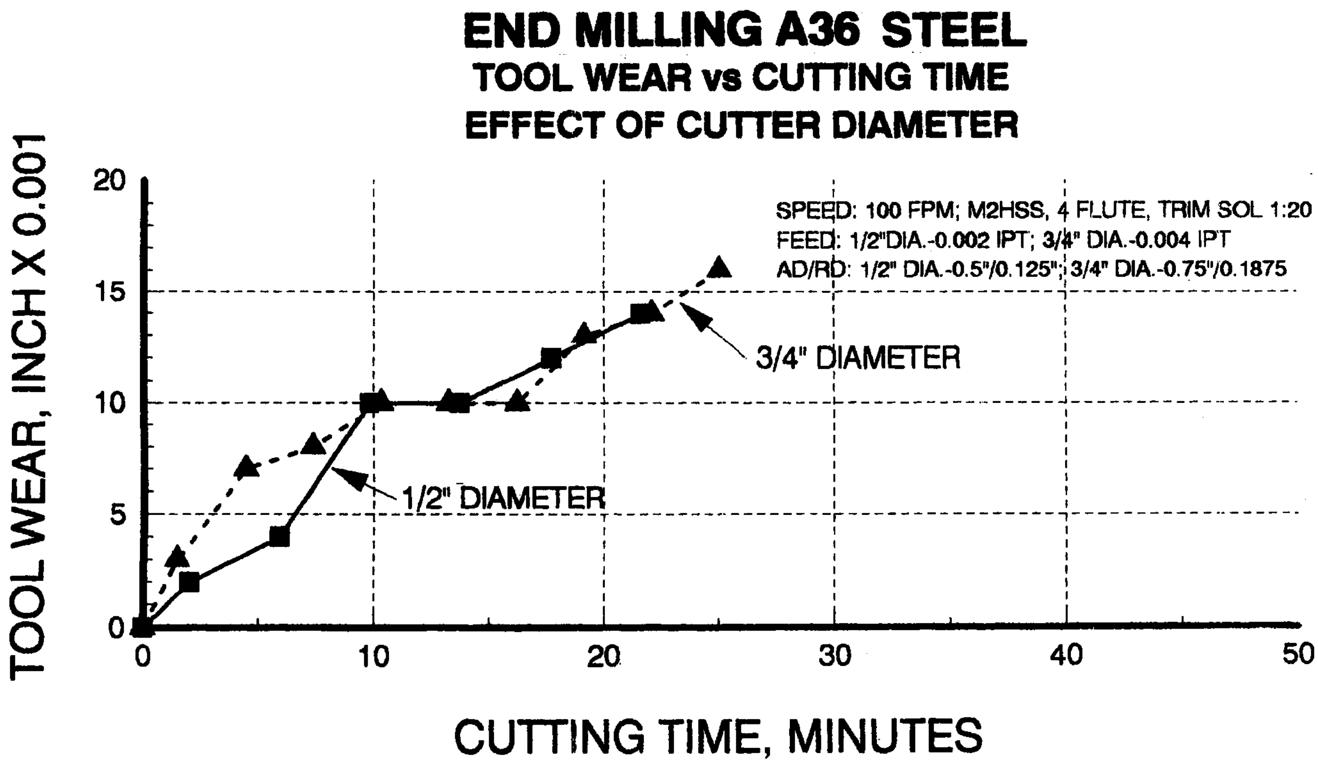


*Figure 46.* The comparison of tool wear vs. cutting time for ½" and ¾" diameter 4-flute end mills made of M2 high speed steel using a cutting fluid when machining A36 steel. The tool life for ¾" diameter end mills was virtually equivalent to the performance of ½" diameter mills.

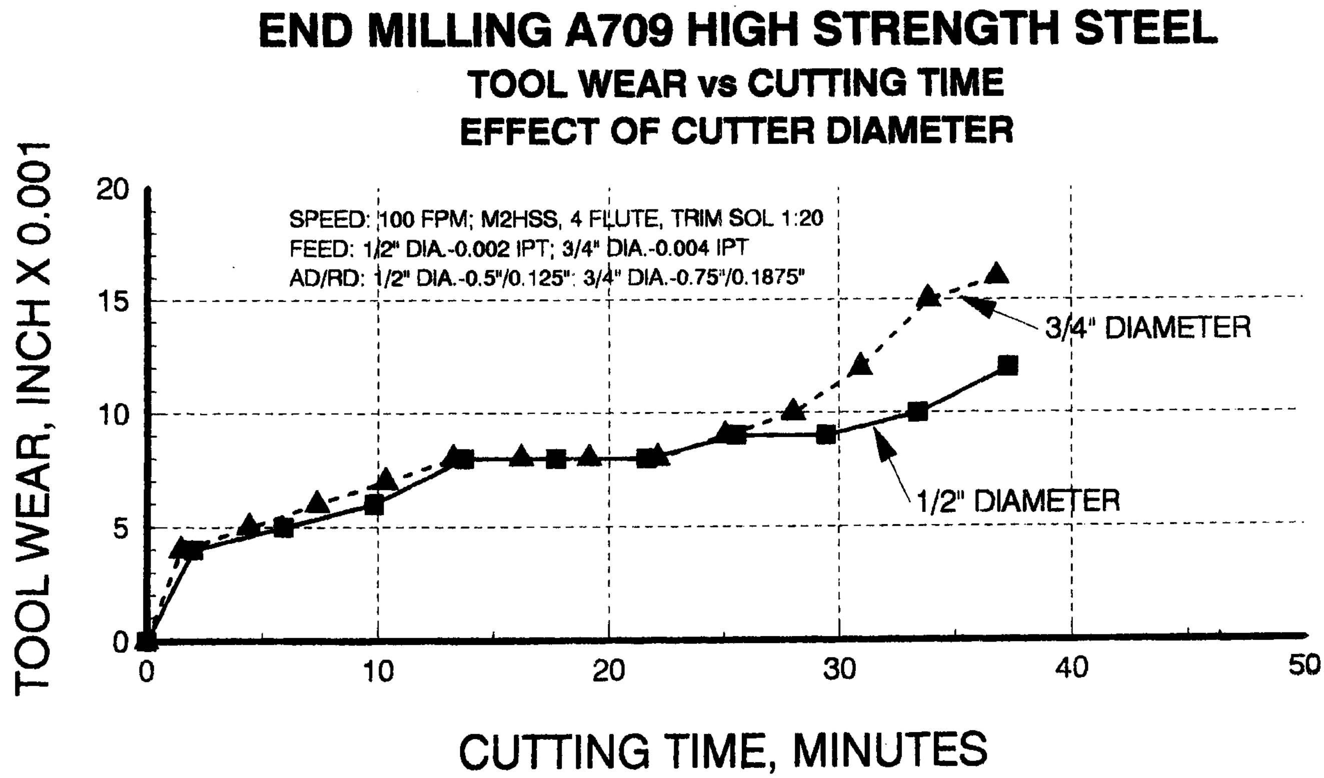


*Figure 47.* The comparison of tool wear vs. cutting time for ½" and ¾" diameter 4-flute end mills made of M2 high speed steel using a cutting fluid when machining A709 HP 70W steel. The tool life for ¾" diameter end mills was equivalent to the performance of ½" diameter mills, except for a steeper rise in wear for the ¾" diameter end mill after 25 minutes of operation.

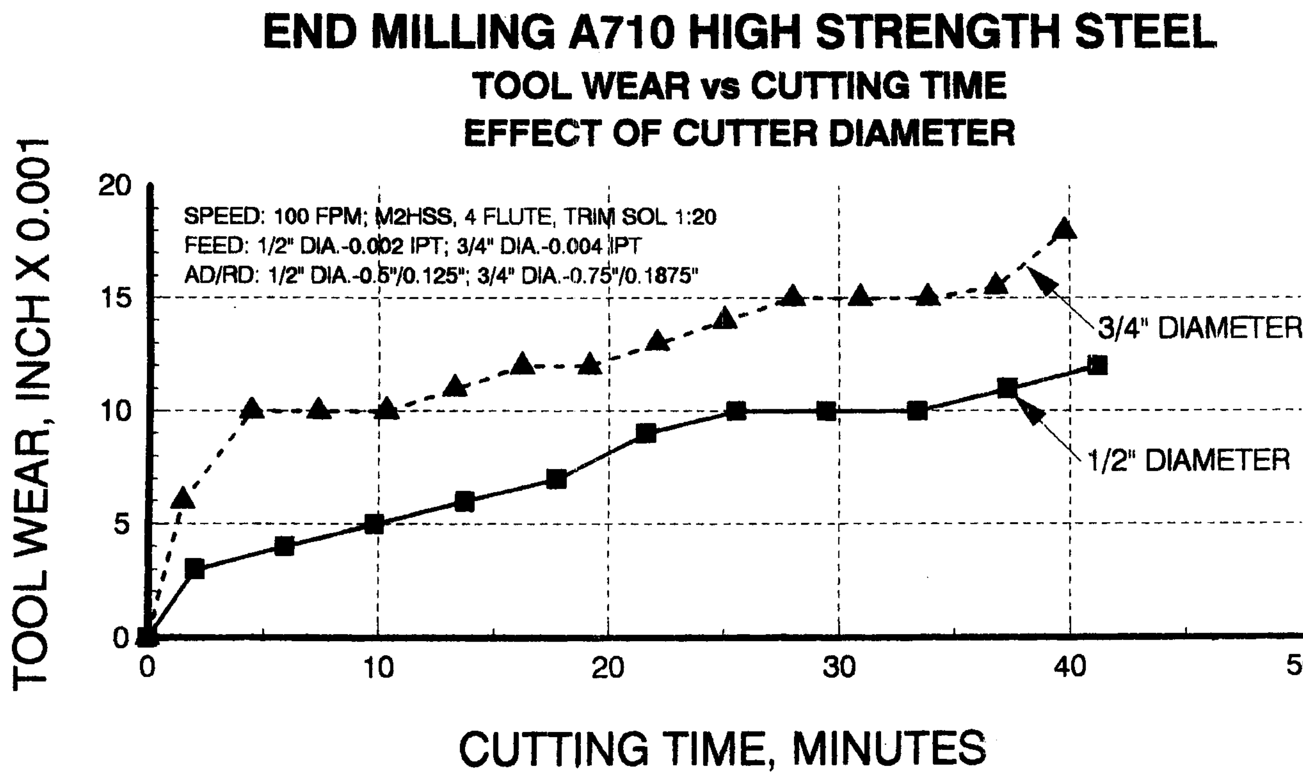


*Figure 48.* The comparison of tool wear vs. cutting time for ½" and ¾" diameter 4-flute end mills made of M2 high speed steel using a cutting fluid when machining A710 Grade B steel. Although the gradual rise in tool wear is parallel for both diameters, the tool wear for ¾" diameter end mills was 50% greater at all times of operation than that of the ½" diameter mills.

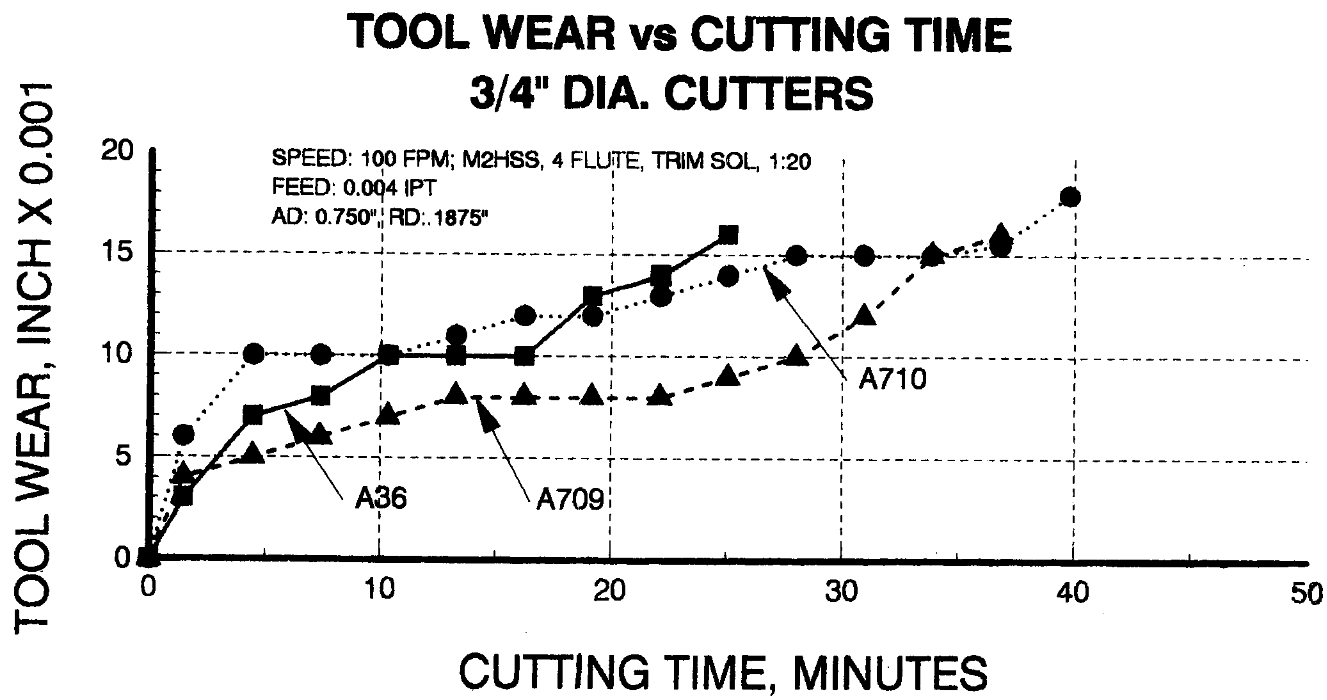


*Figure 49.* The comparison of tool wear vs. cutting time for ½ inch and ¾ inch diameter 4 flute end mills made of M2 high speed steel using a cutting fluid when machining A709 HPS 70W steel. The tool life for ¾ inch diameter end mills was equivalent to the performance of ½ inch diameter mills, except for a steeper rise in wear for the ¾ inch diameter end mill after 25 minutes of operation.

*(4). Metal Removal*

The total metal removed is used to compare the ½ inch end mill with the ¾ inch end mill for the three steels in *Figures 50, 51, and 52.* The difference, using cubic inches instead of cutting time, is much more dramatic between the two sizes of end mills. In *Figure 50,* the ¾ inch end mill removed about three times the material as the ½ inch diameter end mill. *Figure 51* shows that the ¾ inch end mill produced one and one-half times the metal removed by the ½ inch end mill on the A709 steel. Although the ¾ inch end mill removed much more material than the ½ inch cutter before reaching the target amount of corner wear, the advantage was slight for equivalent wear of 0.012 inch in *Figure 52.*

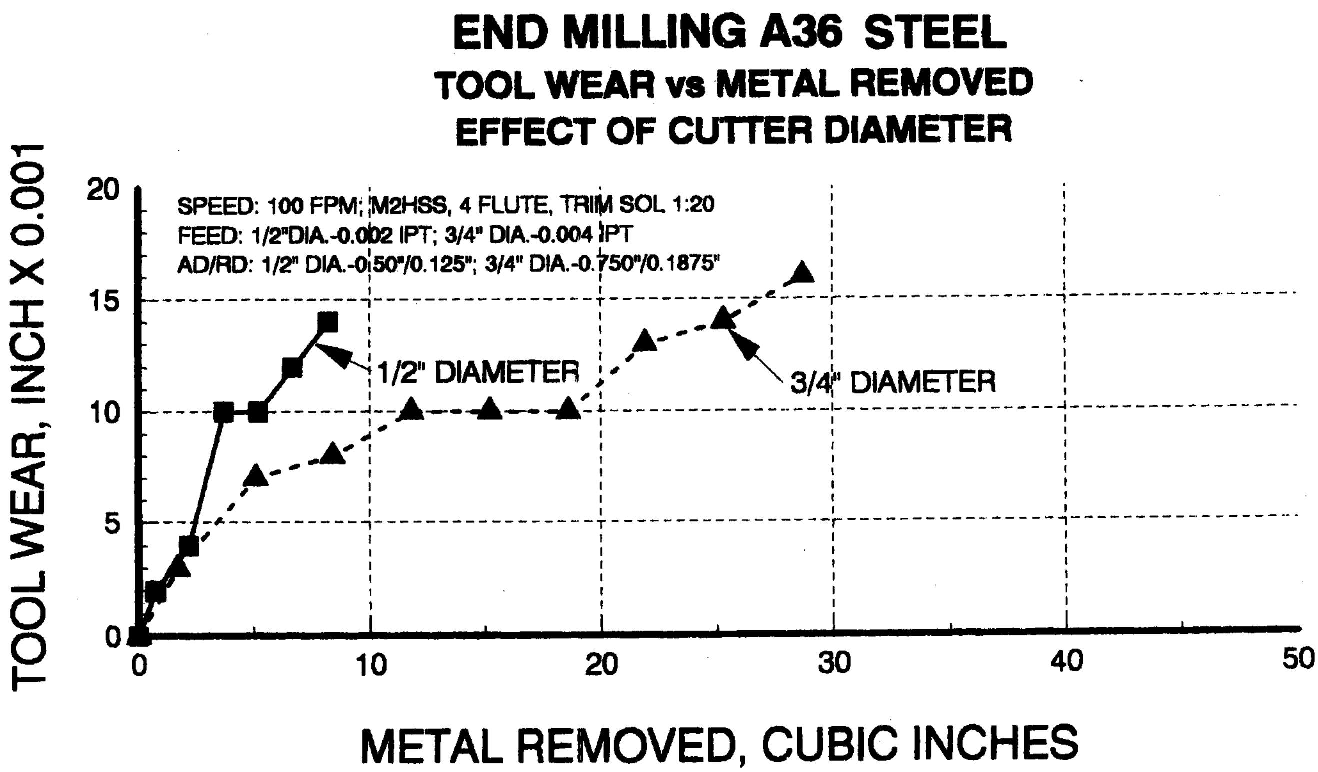


*Figure 50.* The comparison of tool wear vs. metal removed in cubic inches for ½ inch and ¾ inch diameter 4 flute end mills made of M2 high speed steel using a cutting fluid when machining A36 steel. The tool wear for ¾ inch diameter end mills was substantially better than the performance of ½ inch diameter mills. After about 9 $in^3$ of A36 steel removed by the ½ inch end mill, tool wear was 0.014 inch. In contrast, the ¾ inch diameter cutter removed more than 3 times as much A36 steel for the same amount of wear.

The cost of the ¾ inch diameter M2 HSS is about 1.7 times as much as the ½ inch equivalent. The price ratio is about the same for M42 HSS cutters. The price increase is more justified when higher metal removal rate cubic inches / minute ($in^3$/min) of the ¾ inch end mill is realized. Reducing the time to machine a part invariably reduces the cost of the part. Cutting time (labor + overhead) is the highest cost driver in machining. Increasing productivity lowers the cost.

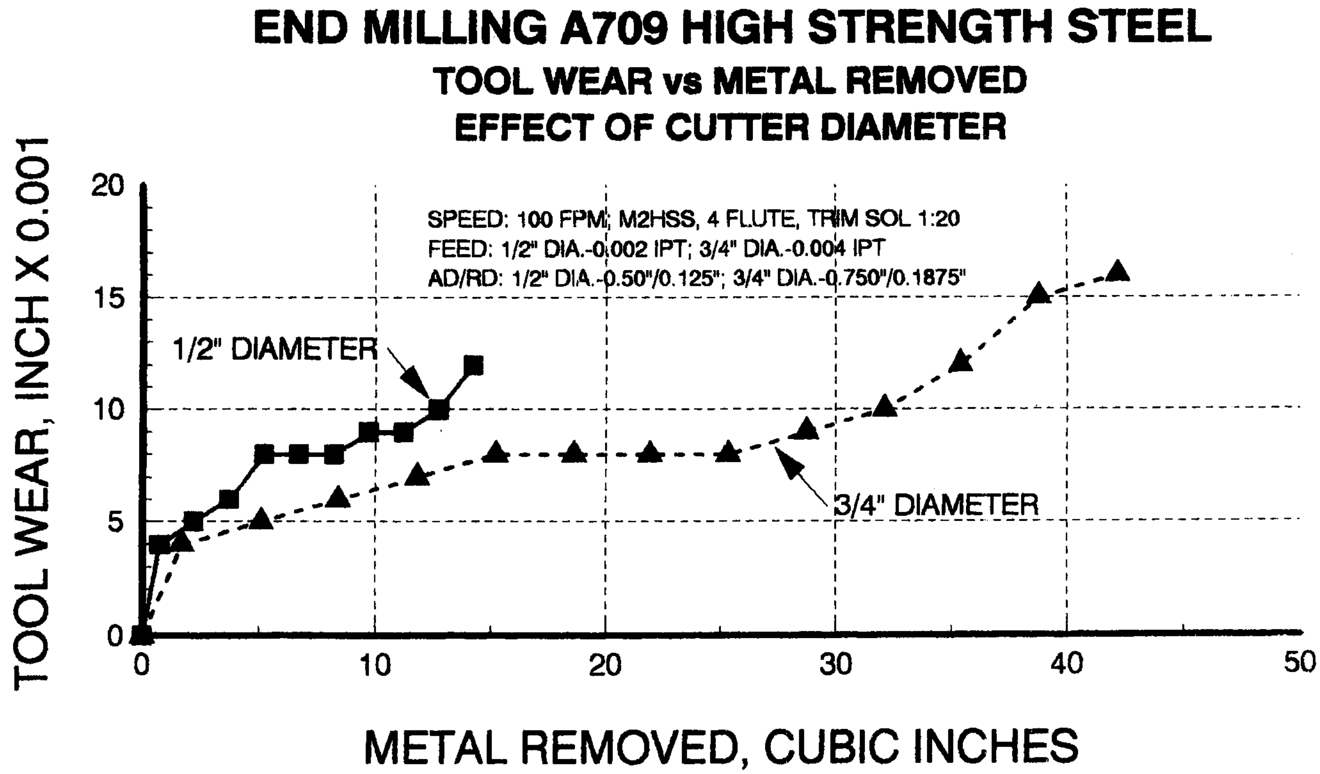


*Figure 51.* The comparison of tool wear vs. metal removed in cubic inches for ½" and ¾" diameter 4-flute end mills made of M2 high speed steel using a cutting fluid when machining A709 HP 70W steel. The tool wear for ¾" diameter end mills was markedly better than the performance of ½" diameter mills. After about 12 $in^3$ of A36 steel removed by the ½" end mill, tool wear was 0.012". The ¾" diameter cutter also removed more than 3 times as much A709 steel for the same amount of wear.

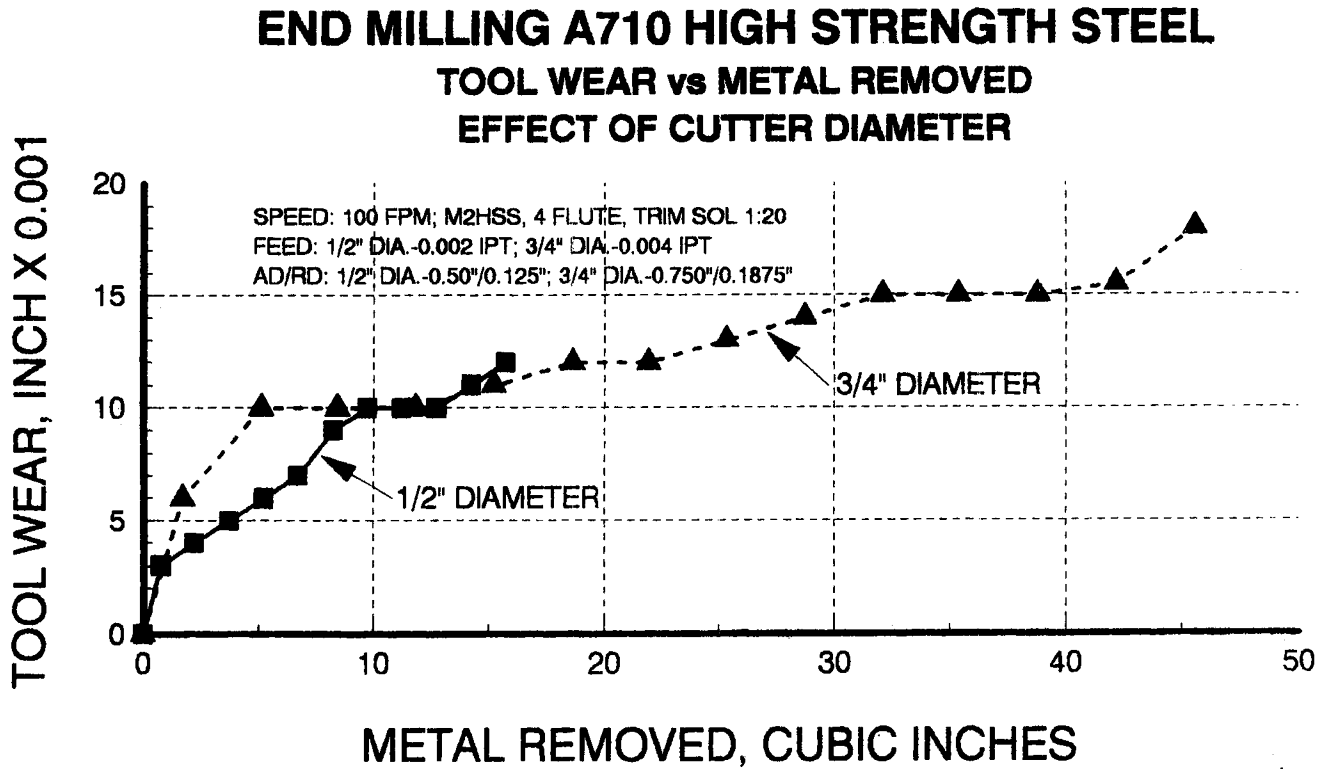


*Figure 52.* The comparison of tool wear vs. metal removed in cubic inches for ½" and ¾" diameter 4-flute end mills made of M2 high speed steel using a cutting fluid when machining A710 Grade B steel. The tool wear for ¾" diameter end mills was substantially equivalent to the performance of ½" diameter end mills. The machining of additional A710 steel sustained more wear on the ¾" diameter end mill after 22 $in^3$ of metal was removed, whereas the ½" diameter mill had 0.012" of corner wear after machining away about 16 $in^3$ of A710 steel.

*Figures 53 and 54* show all three steels with 1/2" and 3/4" end mills respectively. With each size of cutter the A710 steel had the highest metal removed, while the A36 steel had the lowest amount.

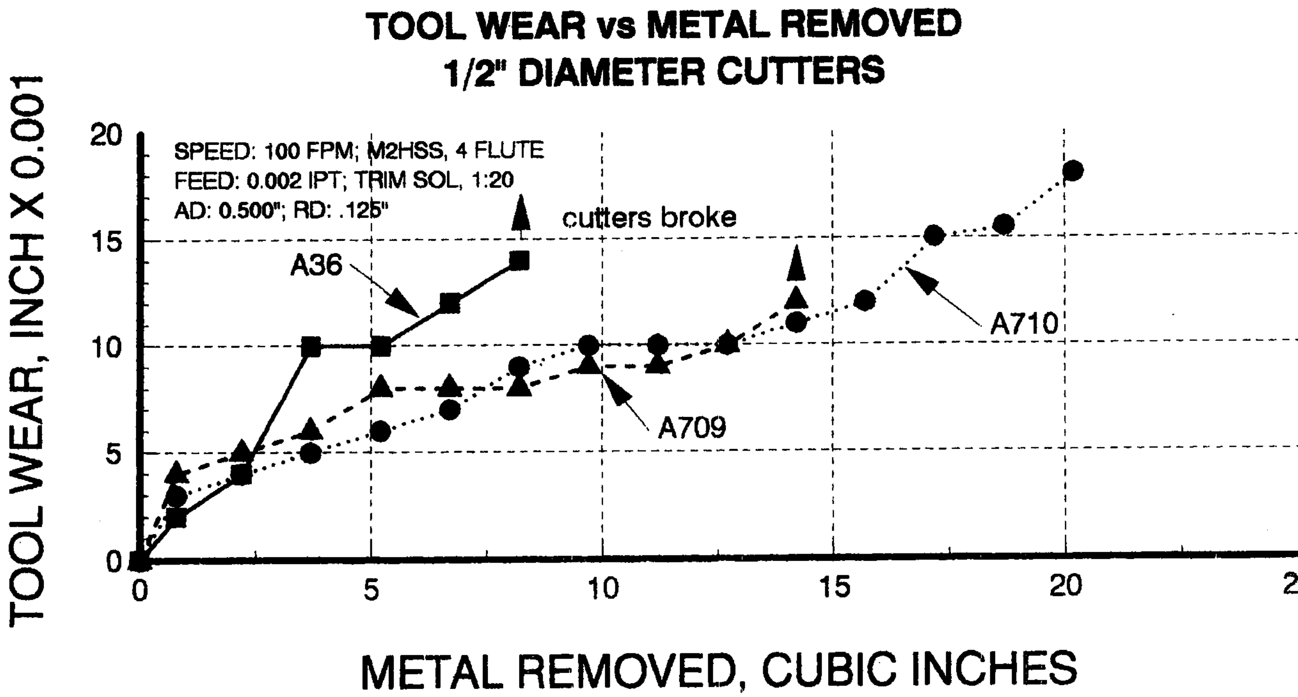


*Figure 53.* A summary comparison of all three steels, using tool wear vs. metal removed in cubic inches for ½" diameter 4-flute end mills made of M2 high speed steel as basis parameters. The tool wear for ½" diameter end mills was substantially equivalent for the HP steels. The machining of additional A36 steel sustained double the amount of wear after only 3 $in^3$ of metal was removed compared to the HP steels. Afterwards, the ½" diameter cutters broke after 7 $in^3$ of metal had been machined away.

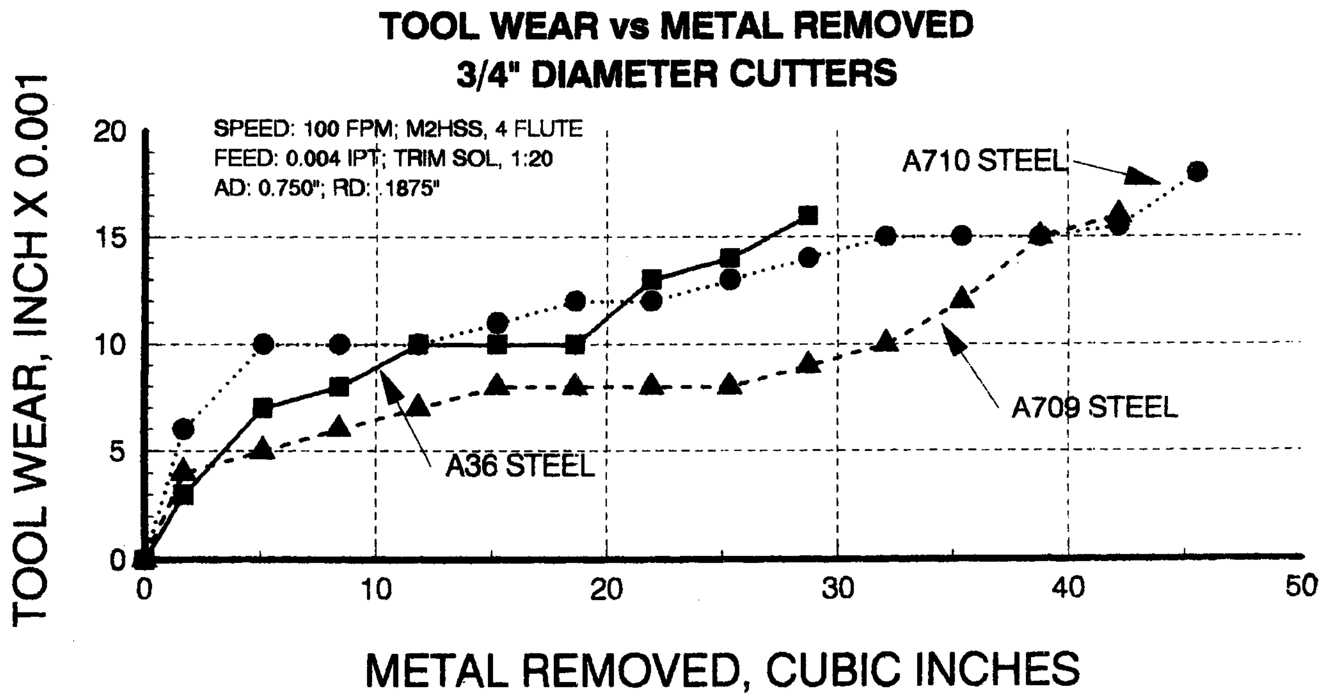


*Figure 54.* A summary comparison of all three steels using tool wear vs. metal removed in cubic inches for ¾" diameter 4-flute end mills made of M2 high speed steel as basis parameters. The A709 HP 70W steel had the least tool wear for ¾" diameter end mills. The end milling of the A710 and A36 were largely parallel and equivalent, although the A710 and A709 coincided after 40 $in^3$ of metal was removed.

*(5). End Mills of ¾" Diameter and A710 Steel*

The A710 steel, which consistently showed the best machinability, was selected to compare the effects of the various 3/4" diameter cutters. *Figure 55* shows a surprising comparison between the M2 and the M42 HSS. Although the M42 HSS is more wear resistant, it is also more brittle. In this example the corners of the M42 cutter chipped excessively, reducing its tool life considerably lower than the life of the M2 HSS cutter.

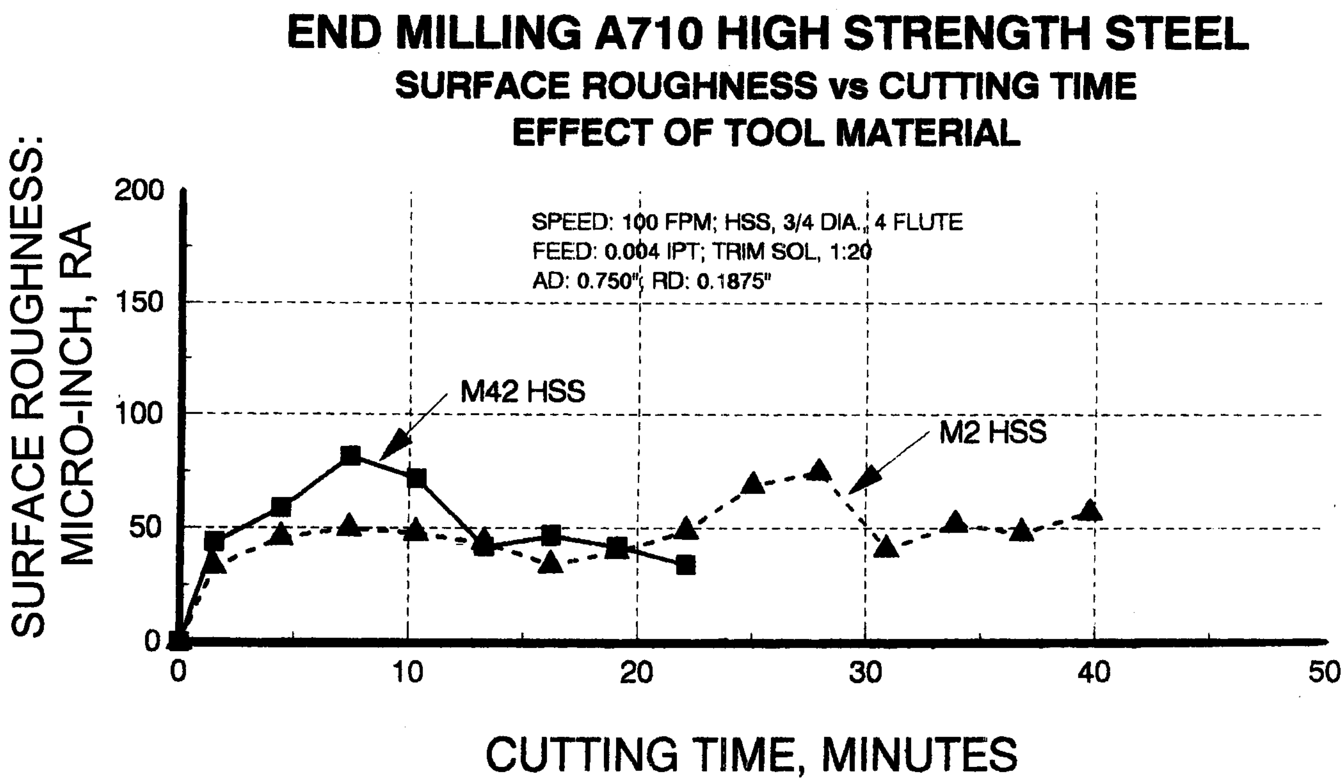


*Figure 55.* A comparison of surface roughness vs. cutting time for ¾" diameter 4-flute end mills made of M2 and M42 high speed steels when cutting A710 Grade B steel. The surface roughness for both the M2 and M42 high speed steels is virtually equivalent as a function of cutting time. Machining with the M42 end mill was halted after 22 minutes due to excessive corner chipping.

*Figure 56* compares the performance of the TiN coated end mill with the M2 HSS standard. The tool life of the TiN coated cutter was so long, it was necessary to lengthen the abscissa on the plot from 50 minutes to 120 minutes. The coated end mill lasted two and one-half times as long as the M2 HSS cutter, while consistently providing lower roughness readings. *Figures 57 and 58* are similar to *Figures 55 and 56,* showing tool wear instead of surface roughness. The inferior, surprising performance of the M42 HSS end mill is shown in Figure 57. The greater performance of the coated end mill is shown in *Figure 58.* The coated end mill costs only 8% more than the M2 HSS end mill. The advantage in performance more than out-weighs the slight cost increase of the coated cutter.

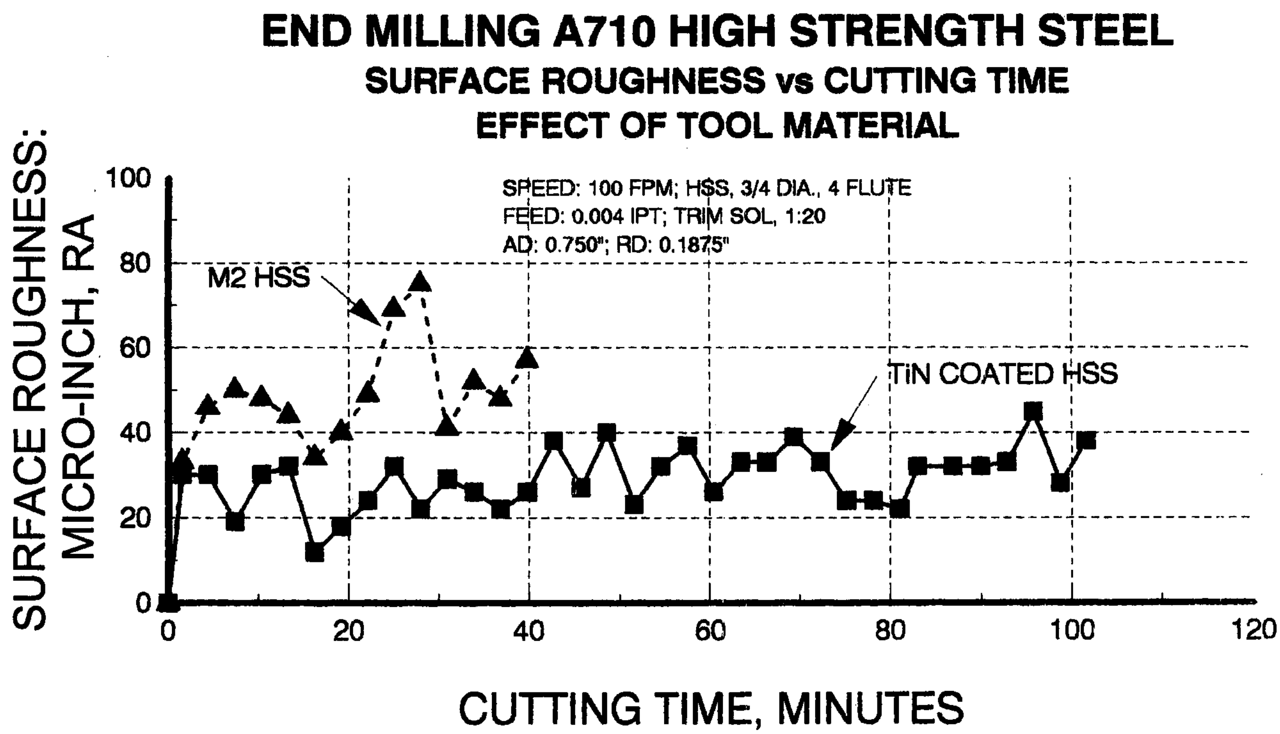


*Figure 56.* A comparison of surface roughness vs. cutting time for ¾" diameter 4 flute end mills made of M2 high speed steel and M2 coated with titanium nitride when cutting A710 Grade B steel. The surface roughness for the M2 various from 2-2.5 times more than the average surface roughness of 30 μin for the coated M2 high speed steel. In addition, its cutting time is markedly longer by a factor of three.

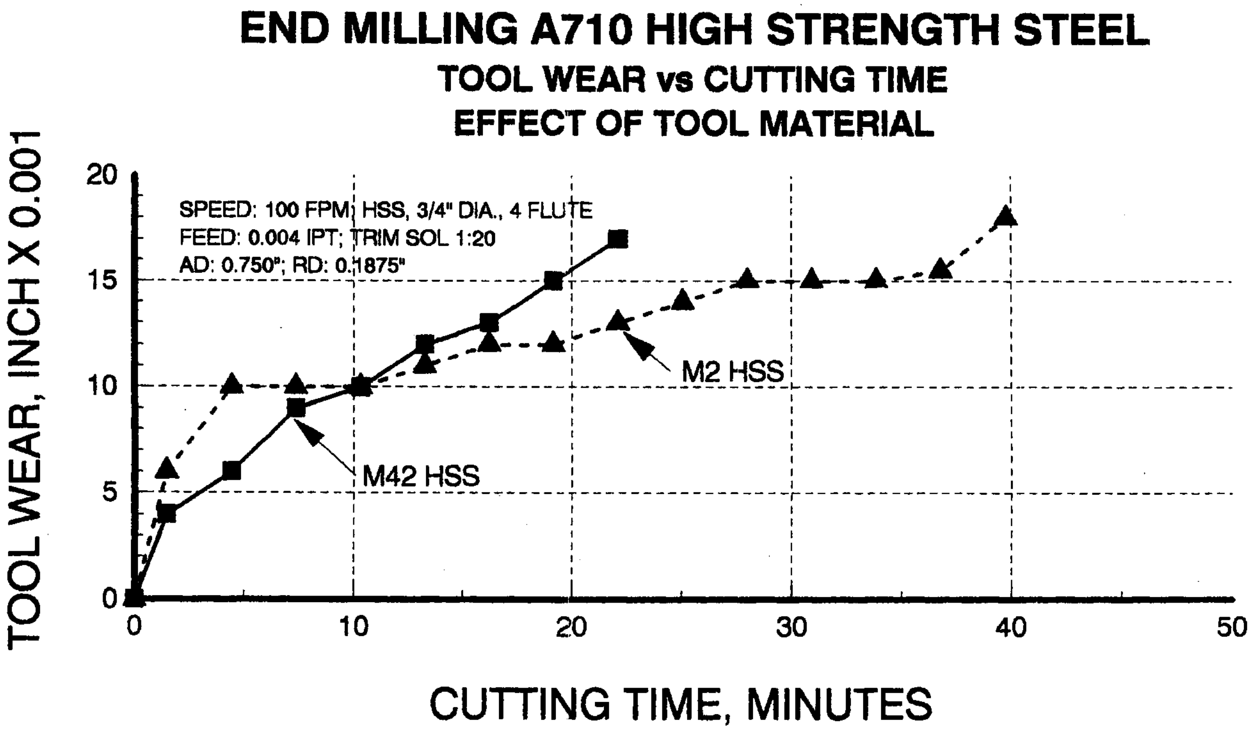


*Figure 57.* A comparison of tool wear vs. cutting time for ¾ inch diameter 4 flute end mills made of M2 and M42 high speed steels when cutting A710 Grade B steel. The tool wear for both the M2 and M42 high speed steels are parallel and fairly equivalent up to 10 minutes of operation. Afterwards, the M42 wear starts to significantly increase, whereas the M2 has a soft rise and plateau at about 30 minutes, but ultimately sustains 0.017 inch of wear after 40 minutes.

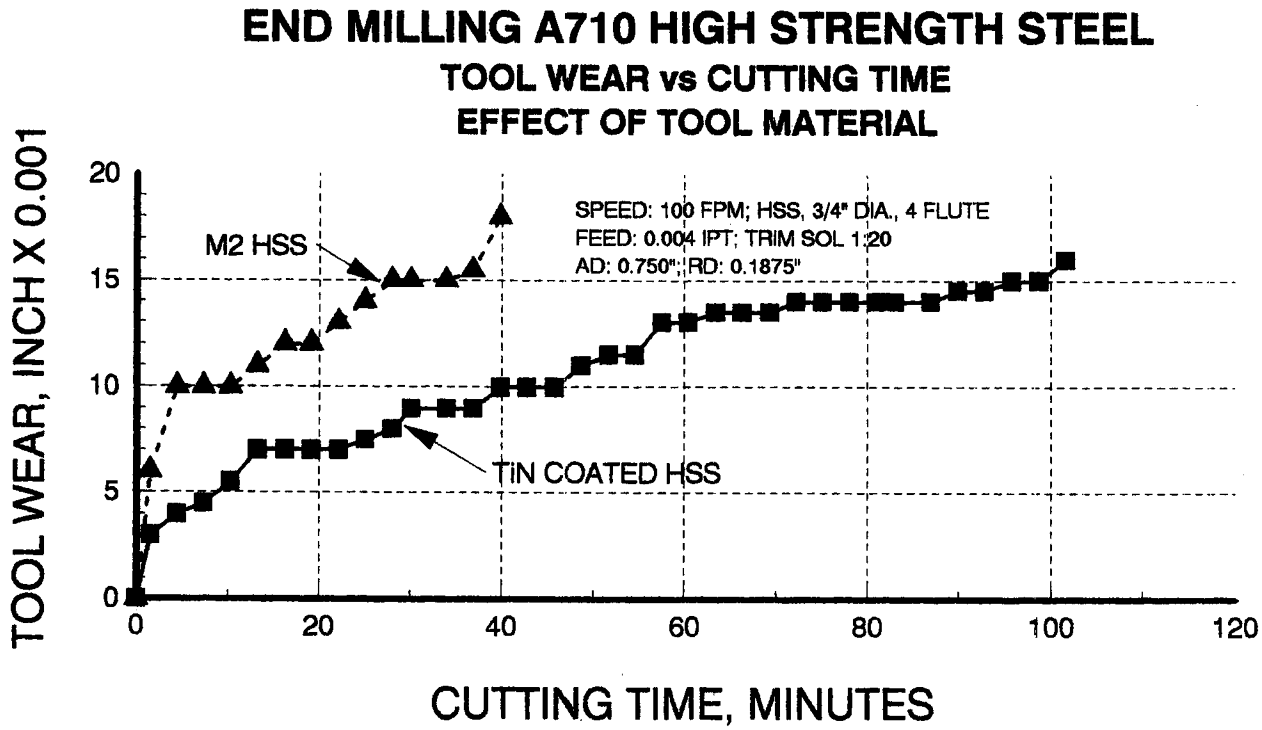


*Figure 58.* A comparison of tool wear vs. cutting time for ¾ inch diameter 4 flute end mills made of M2 high speed steel and M2 coated with titanium nitride when cutting A710 Grade B steel. The tool wear for the M2 , although parallel in slope of wear vs. time, has a magnitude about twice as much as the wear sustained by the coated M2 high speed steel. In addition, the cutting time of the coated M2 end mill is about 2.5 times longer than the M2 high speed steel mill.

*Figures 59, 60, and 61* all compare the performance of the M2 HSS 3 flute end mill with the 4 flute cutter. In *Figure 58,* the roughness readings are about the same with both types of end mill. *Figure 60* shows that the 4 flute end mill cut about 27% longer for the same level of tool wear. *Figure 61* gives a more clear advantage of the 4 flute end mill over the 3 flute cutter. The 4 flute end mill removed about 75% more metal than the 3 flute end mill. The two types of end mill cost about the same amount, although the 4 flute end mills are much more commonly available.

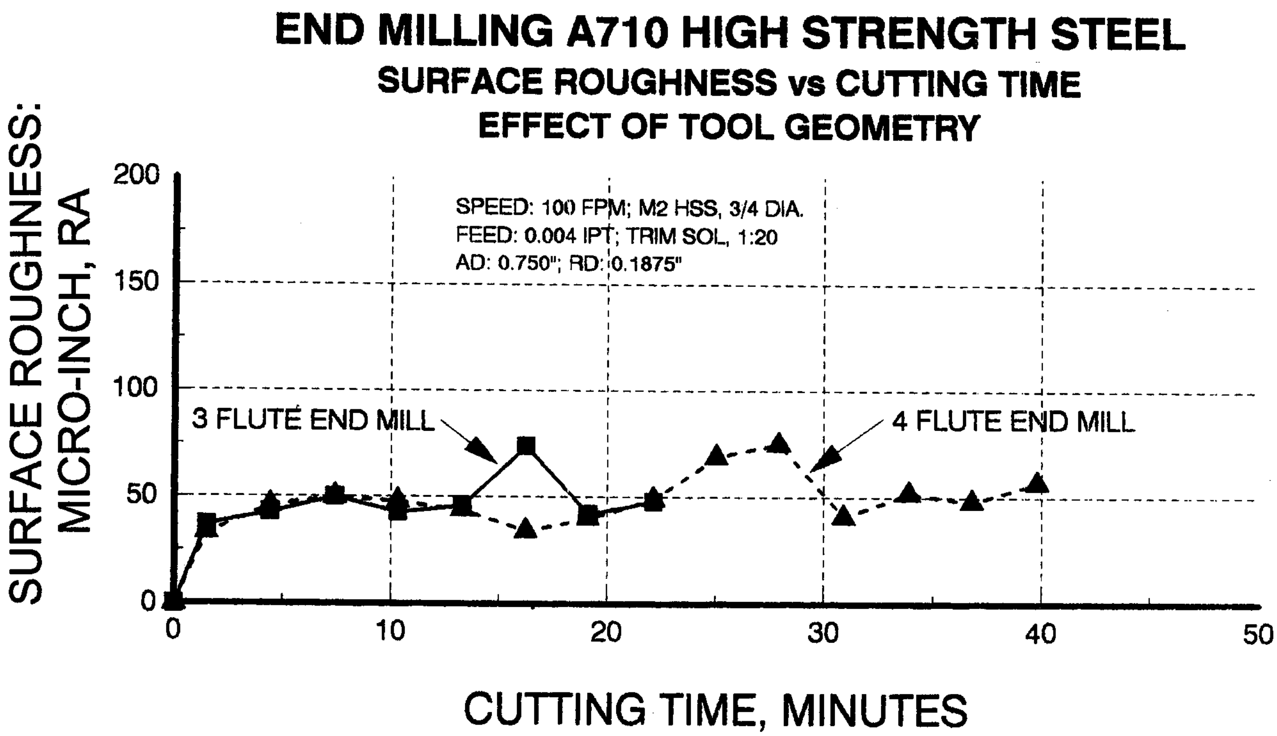


*Figure 59.* A comparison of surface roughness vs. cutting time for 3 and 4 flute ¾" diameter end mills made of M2 high speed steel when cutting A710 Grade B steel. The surface roughness for each of these end mills is virtually equivalent, with the 4-flute mill sustaining about twice the life in operation and still maintaining an average surface roughness of about 50 μin.

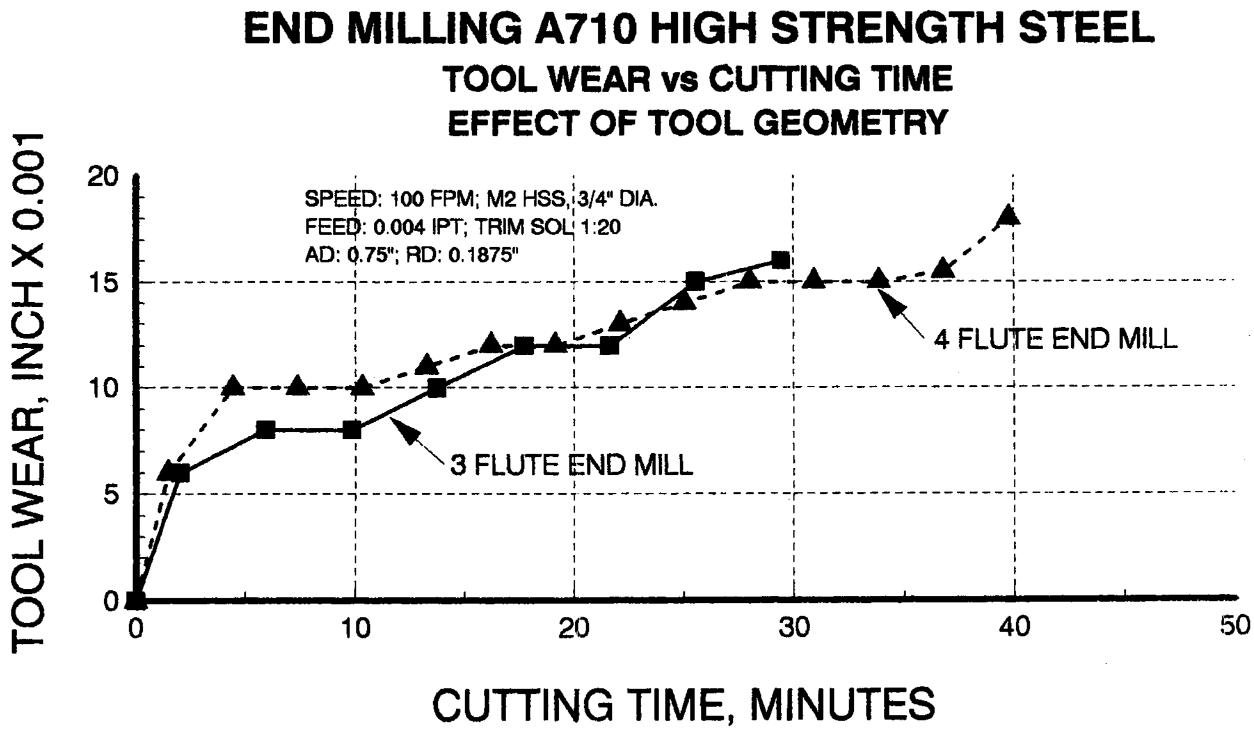


*Figure 60.* A comparison of tool wear vs. cutting time for 3 and 4 flute ¾" diameter end mills made of M2 high speed steel when cutting A710 Grade B steel. The surface roughness for each of these end mills is also virtually equivalent, with the 4-flute mill sustaining about 37% more tool life the life in operation than the 3-flute mill with an average corner tool wear of about 0.015".

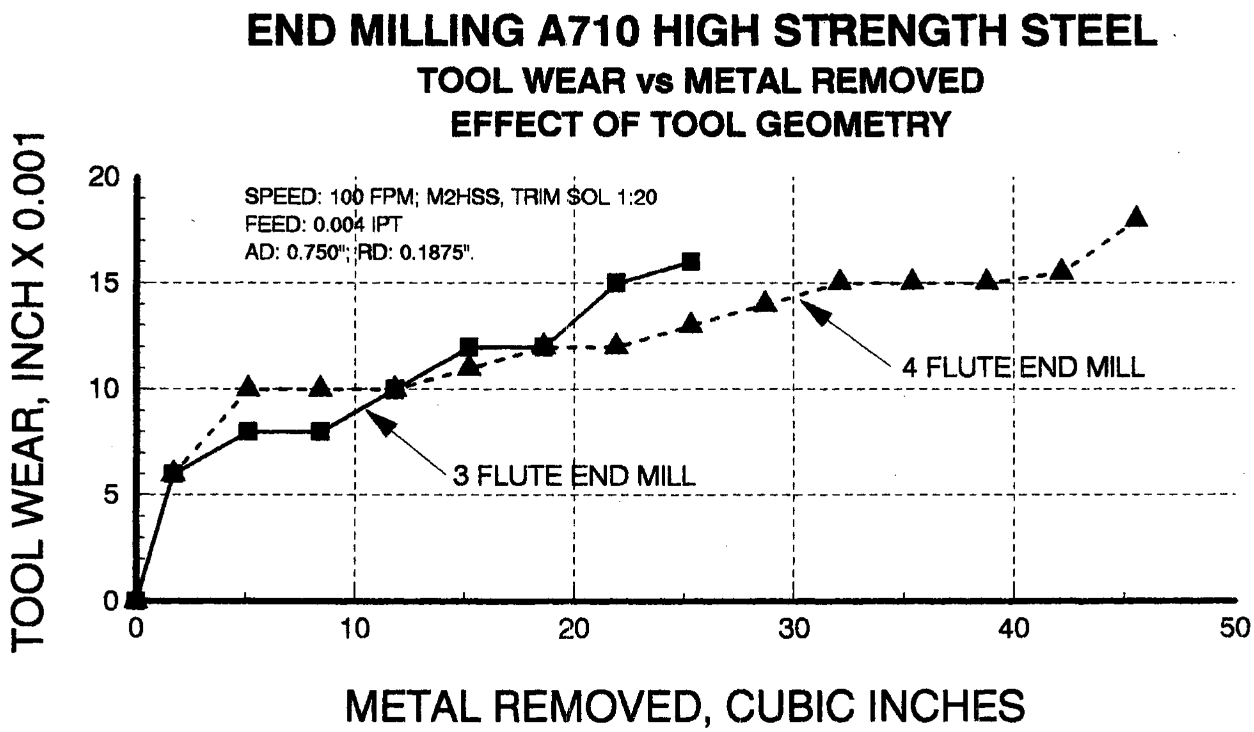


*Figure 61.* A comparison of tool wear vs. metal removed for 3 and 4 flute ¾" diameter end mills made of M2 high speed steel when cutting A710 Grade B steel. The surface roughness for each of these end mills is virtually equivalent until about 18 in3 of A710 steel is removed, after which the 3-flute end mill sustains a rise in wear. The 4-flute mill removes at least 22 in3 more of material, until tool wear at this point increases sharply, upon which the test was terminated.

*(6). Solid Carbide End Mills*

*Text Table 4* lists the results of end milling A710 steel with solid carbide end mills. One end mill was coated with titanium nitride (TiN) and the other was uncoated. The designation "carbide" for tool steels in the United States indicates a cutting material typically consisting of very hard carbides in an iron-cobalt matrix. The SAE also has a classification system for super hard tool materials in SAE Standard J1072. The super hard carbides incorporated can include the carbides of titanium, vanadium, columbium, chromium or tungsten.

Suffixes in the US C-Grade System designate the application of the carbide, such as whether it has finishing characteristics, or is intended for wear-resistant surfaces, or those that will encounter impact during machining. C-1 to C-4 carbides are used for general purpose machining of cast irons, non-ferrous alloys and non-metallic materials. C-5 to C-8 carbides are used primarily used for general purpose machining of carbon and alloy steels. The C-2 and C-6 carbides used in this study are for general purpose machining. The compositions of these grades are not standardized, and are dependent on manufacturer preference.

*Text Table 4* / END MILLING A710 STEEL

Time and Wear on Surface Roughness Using Solid Carbide End Mills

Cutter: Atrax Brand ½ inch Dia., 4 Flute End Mill, Micrograin Carbide
Cutting Speed/Feed Rate: 350 fpm @ 0.002 ipt
Axial Depth of Cut: 0.500 inch (1x Dia.)
Radial Depth of Cut: 0.125 inch (Dia./4)
Cutting Fluid: TRIM SOL, 1:20
Setup of Cutter to Work piece: Climb milling

| Corner Wear, inch | Cutting Time, min. | Average Surface Roughness, μin |
|---|---|---|
| 0.001 | 0.56 (12 inch) | 33 |
| 0.002 | 1.68 (36 inch) | 34 |
| 0.004 | 2.15 (46 inch) * | 80-101 |

* The end mill broke at this point; 2 corners were chipped off.

The micro-carbide grade used in this study was of micro-grain morphology, which uses a much finer particle size of carbide and about twice (12%) as much cobalt binder. Micro-grain carbide tools have much higher transverse rupture strength than C-2 or C-6 grades, which are the more common machining grades. Higher transverse rupture strength roughly translates into a tougher cutting edge on the tool. The tougher cutting edge resists chipping, which often occurs in an interrupted cutting process such as face milling or end milling. This type of carbide cutter, which should be most suitable for this operation, unfortunately did not perform satisfactorily.

The solid micro-grain carbide end mill started well, but did not last. The first pass of 12 inch produced no chipping on the periphery or the corners. After three passes, 36 inch, the corners were still not chipped but two of the flutes were chipped. After only ten more inches of cutting, 46 inches total or

2.25 minutes of milling the A710 steel, this cutter failed. Examination of the broken pieces showed two corners completely chipped off. The peripheral cutting edges were also degraded as indicated by the drastic increase in surface roughness readings from 34 μin to 80-101 μin.

The TiN coated carbide end mills also did not perform satisfactorily. After one pass of 12 inches, all four corners of the coated carbide end mill were chipped from 0.008 inch to a severe 0.026 inch. Heavy corner chipping negated further use of this cutter. Past experiences have indicated that catastrophic breakage will likely soon occur when the corners are heavily worn or chipped. It is speculated that the coating process degraded the integrity of the carbide on the corners where the mass is small, weakening the corners.

The identical solid carbide end mill, coated with TiN made only one pass, 12 inches, and all four corners were severely chipped from 0.016 inch to 0.026 inch. Apparently, the coating process used to apply the TiN coating on this end mill also weakened the corners of this cutter. The impact of the interrupted cutting on these corners caused heavy chipping. When the corner damage is this heavy, the cutter usually breaks catastrophically within a short period of time. This happened a few times with the ½ inch dia. HSS end mills. The carbide end mills are considerably more brittle and have lower in transverse rupture strength than high speed steel. Transverse toughness has a rough correlation to the relative toughness of the tool material.

It is possible that carbide insert type end mills, which have a totally different geometry, may successfully cut these steels. There are so many grades and shapes of inserts and holders that testing or evaluating this type of cutter was beyond the scope of this project.

*(7). Carbide vs. High Speed Steel End Mill Comparison*

In general, based on the results obtained, the standard grade of HSS is preferred over the premium M42 grade which has 8% cobalt. The added cost does not always provide a significant increase in tool life. However, the titanium nitride coated HSS tool is recommended for longer tool life. For situations where heavier metal removal rates are required, ¾ inch diameter end mills were preferred over ½ inch diameter end mills. Cutters of ½ inch diameter will more readily break under increased tool wear, whereas ¾ inch diameter cutters generally will not. Solid carbide end mills were not recommended at this time until the edge breakage problem has been resolved.

## 7. GRINDING

As in the previous tests, the same three steels were evaluated in the grinding portion of this contract. The test samples of A36 and A709 were 1 inch thick by 12 inches by 5 inches. The A710 sample was ½ inch thick by 12 inches by 5 inches. All samples were ground on both sides prior to testing to insure a true, flat surface for measurements.

### *A. Machine Tool and Measurements*

The grinding tests were performed on an Acer Brand Model 1224AHD 5 horsepower surface grinder. This machine was equipped with a variable speed spindle drive and an automatic incremental down feed. The work piece table, which has an electro-magnetic chuck, is 12 inches wide and 24 inches long.

The surface roughness or finish readings were taken on a Federal Brand Pocket Surf portable surface roughness gage. The advantage of this instrument is its flexibility and versatility. Measurements were made while the work piece fixtured, chucked, or clamped in the machine tool, and does not require the work piece to be removed to a bench for setup. A calibration standard was included to insure the accuracy of the surface roughness measurements.

### *B. Test Conditions*

The target surface roughness conditions were 32, 16, and 8 µin surface roughness finishes. These surface roughness values were in correspondence with the appropriate material removal rates to obtain those readings. The reciprocating table speed of the grinder was a maximum of 84 fpm. All grinding was performed dry without coolant. The wheel speed was 1780 rpm, or 5,824 fpm if taken circumferentially on a wheel diameter of 12.5 inches. Most surface grinders are set to run at approximately 6,000 fpm if they are not equipped with a variable speed spindle drive.

The grinding wheel used for these tests was a 100 grit aluminum oxide wheel, designated as 9A100I8V52. This wheel was recommended for finish grinding to obtain the 8 and 16 µin readings. A review of several years of surface grinding data revealed that only aluminum oxide ($Al_2O_3$) wheels are used on steels.

Silicon carbide wheels are recommended for all types of nonferrous alloys with few exceptions. Some of these exceptions are austenitic stainless steels, gray and compacted graphite cast iron, ductile, malleable and white cast irons, where both $Al_2O_3$ and silicon carbide wheels are used.

The *Machining Data Handbook*, the only exhaustive publication of recommendations for machining and grinding, supports these selections of grinding media. For this reason, an aluminum oxide wheel was used for all these tests.

It is a common but undesirable practice to fine-dress the grinding wheel with a diamond dresser to produce low surface roughness readings. This practice is not recommended, because a finely-dressed wheel is a *dull wheel*, which will load up quickly with cut material and alumina and possibly induce high tensile stresses into the surfaces of the work piece.

This can represent a potentially dangerous condition if the work piece is ever subjected to critical alternating stresses, even at low cycle frequencies. The presence of high surface tensile stresses and any surface discontinuity, such as a fastener hole, sharp corner or step in a shaft, can become a potential crack initiation site. Once a crack initiates, it can grow and generate a fatigue failure under alternating stresses or a sufficiently high static stress if the crack length is long enough. This fracture critical condition occurs if the crack length and the stress level exceed the critical fracture toughness, which is expressed in inch-pound units of ksi $[in]^{1/2}$.

If possible, grinding wheel speeds should be at a maximum of 4000 ft/min for finish grinding conditions to minimize stress. The publication *Low Stress Grinding for Quality Production* (Ref C) should be consulted to adjust all the grinding parameters to insure the absence of high tensile residual stresses in the surface of the ground work piece.

### *C. Test Results*

*Text Table 5* illustrates the surface roughness readings in micro-inches produced with a variety of grinding conditions. These results indicate that obtaining surface roughness readings of 32, 16, and 8 µin finishes are readily obtainable with a 100 grit aluminum oxide grinding wheel, using down feed and cross feed values in the ranges shown in *Text Table 5.*

As was expected, the roughness readings taken perpendicular to the direction of the table travel are usually higher than the readings taken parallel to the table travel. A general "rule-of-thumb" is that the perpendicular readings are about 1.5 to 2 times higher than the parallel readings.

*Text Table 5* / SURFACE ROUGHNESS BY GRINDING

| Down Feed in/pass | Cross Feed in/pass | Surface Roughness Readings, μin parallel to lay | perpendicular to lay |
|---|---|---|---|
| | | ASTM A36 Steel | |
| 0.0005 | 0.030 | 4, 5 | 16, 22 |
| 0.0010 | 0.030 | 16, 28 | 8, 15 |
| 0.0015 | 0.030 | 4, 5, 6 | 14, 16 |
| 0.0020 | 0.030 | 16, 20 | 12, 16 21 |
| 0.0005 | 0.130 | 8, 11, 12 | 17, 22, 24 |
| 0.0010 | 0.130 | 4, 7, 10 | 13, 16, 17 |
| 0.0020 | 0.130 | 12, 19, 9 | 9, 20, 37 |
| | | ASTM A709 HPS 70W Steel | |
| 0.0005 | 0.030 | 15, 17, 7 | 27, 27, 30 |
| 0.0010 | 0.030 | 13, 11, 10 | 19, 18, 20 |
| 0.0015 | 0.030 | 4, 6, 7 | 19, 21, 22 |
| 0.0020 | 0.030 | 6, 6, 5 | 18, 20, 22 |
| 0.0005 | 0.130 | 10, 11, 13 | 28, 25, 29 |
| 0.0010 | 0.130 | 6, 7, 9 | 26, 25, 35 |
| 0.0020 | 0.130 | 15, 10, 13 | 53, 49, 39 |
| | | ASTM A710 Grade B Steel | |
| 0.0005 | 0.030 | 5, 7, 6 | 11, 14, 14 |
| 0.0010 | 0.030 | 4, 4, 5 | 16, 12, 14 |
| 0.0015 | 0.030 | 8, 7, 7 | 17, 16, 14 |
| 0.0020 | 0.030 | 6, 7, 11 | 14, 13, 17 |
| 0.0005 | 0.130 | 17, 15, 9 | 21, 23, 25 |
| 0.0010 | 0.130 | 11, 16, 8 | 27, 19, 25 |
| 0.0020 | 0.130 | 12, 8, 9 | 21, 34, 22 |

In *Text Table 5*, when the "lay" corresponds with the predominant rolling or forging direction of the steel, this ratio can be even higher if the grains are large and not equi-axed, and the mechanical properties are substantially different in the rolling direction vs. the transverse direction. Because the transverse orientation of rolled steel is often subject to banding of pearlite or other axial alignments of non-metallic inclusions, its surface roughness is not as uniform as the rolling direction and literally has alternations of "hills and valleys" of soft and harder material that must be ground down during the grinding operation.

### *D. Grinding Ratios*

Grinding ratios, which are analogous to tool life values in machining, provide a relative indication of the efficiency of the grinding operation. The grinding ratio is defined as the volume of work material removed divided by the volume of grinding wheel consumed in the process. This is a delicate test and requires very careful measurements of the work piece and the grinding wheel diameter. Machining Research had performed dozens of grinding ratio tests over 39 years of machinability testing, and accumulated a great deal of grinding ratio data on a variety of alloys. Most of the steels tested were relatively hard, 40 to 52 on the Rockwell C hardness scale.

Typically, grinding ratios for these hardened steels reach a maximum of 20 to 25. One alloy steel at 300 BHN had grinding ratios from 55 to 133. A grinding ratio of 133 means that for each 1 $in^3$ of grinding wheel consumed, 133 $in^3$ of steel are ground away. At this level, this indicates a highly efficient grinding process.

For grinding operations where high material removal rates are desired and surface roughness is not an important consideration, a 35 grit or 45 grit aluminum oxide grinding wheel would be more efficient than a 100 grit wheel. To obtain finishes with low surface roughness readings, a fine wheel of 100 grit or finer, typically 220 or 320 grit, should be used.

## 8. DRILLING

In order to replicate both field and shop conditions for large hole drilling, the portable Hougen magnetic drill and annular Hougen Rotabroach drills on all three steels, ¾ inch diameter holes were drilled to1 inch depth. Most of the Hougen magnetic drills are hand-feed models, not power-fed. Power-feed Hougen Model No. 10925 uses constant pressure, not positive feed. The feed force is provided by springs, and as the cutter wears, the feeding force is increased and the feed rate slows down. Hand feeding also slows down as the cutter wears. In each case, the slug must be driven out of the Rotabroach cutter after each hole is cut into a 1 inch thick work piece.

There are advantages to the hand-feed model. The operator can easily and instantaneously interrupt the feed, breaking the chips. Since the A36, A709 and A710 steels are relatively soft in the range of 156 to 229 BHN, the chips off the drill are continuous and therefore can present cutting hazards to eyes and hands. Very brief interruptions to the feed and slowing down the drilling only slightly can provide a significantly safer situation for the operator. Safe operation of the magnetic drill requires safety glasses and gloves for the operator.

### *A. Annular Drills*

The ¾ inch diameter Hougen Rotabroach is a 4 flute cutter, with a tooth grind similar to an end mill (Ref G). However, the Rotabroach mills away a ring of material with the center slug sliding up inside the hollow ID of the cutter. Using this technique enables the cutter to "drill-cut" a large diameter hole using only a fraction of the power required of a conventional twist drill, which cuts away the entire cross section of the hole. The end design cuts the largest diameter first and then engages the rest of the ring. This is seen by examining the slugs, which have a small cap on the exit end of the slug.

*Figure 62* shows the tool wear variation among the three cutters used to drill the three steels. As shown in *Figure 62*, there is very little difference between the cutter wear on the A36 steel and the A710 steel. The A709 steel had the highest wear after drilling 10 holes. Only 30 holes were drilled due to the slow nature of this drilling process.

In hand feeding the Hougen cutters through the three steels, it was evident that the feed forces were different. The A36 steel was by far the easiest to feed through the work piece. The A710 steel was noticeably harder than the A36, but the A709 required the most force among the three steels. Cutting forces usually increase with higher tool wear. Since the cutter used on the A709 steel had the highest wear, it should also have the highest cutting forces.

The last "good" hole of each steel was measured to note the quality of the hole walls. Surface roughness measurements were made on each completed hole. The very first holes in the A709 and the A710 steels were below 100 µin. All of the rest of the readings were rougher, with most of them in the 150 to 250 µin range. There is a common occurrence when machining soft steels called built-up-edge (BUE). The main result of BUE is a smearing of the chips on the machined surface, leaving a rough finish on the walls of the holes.

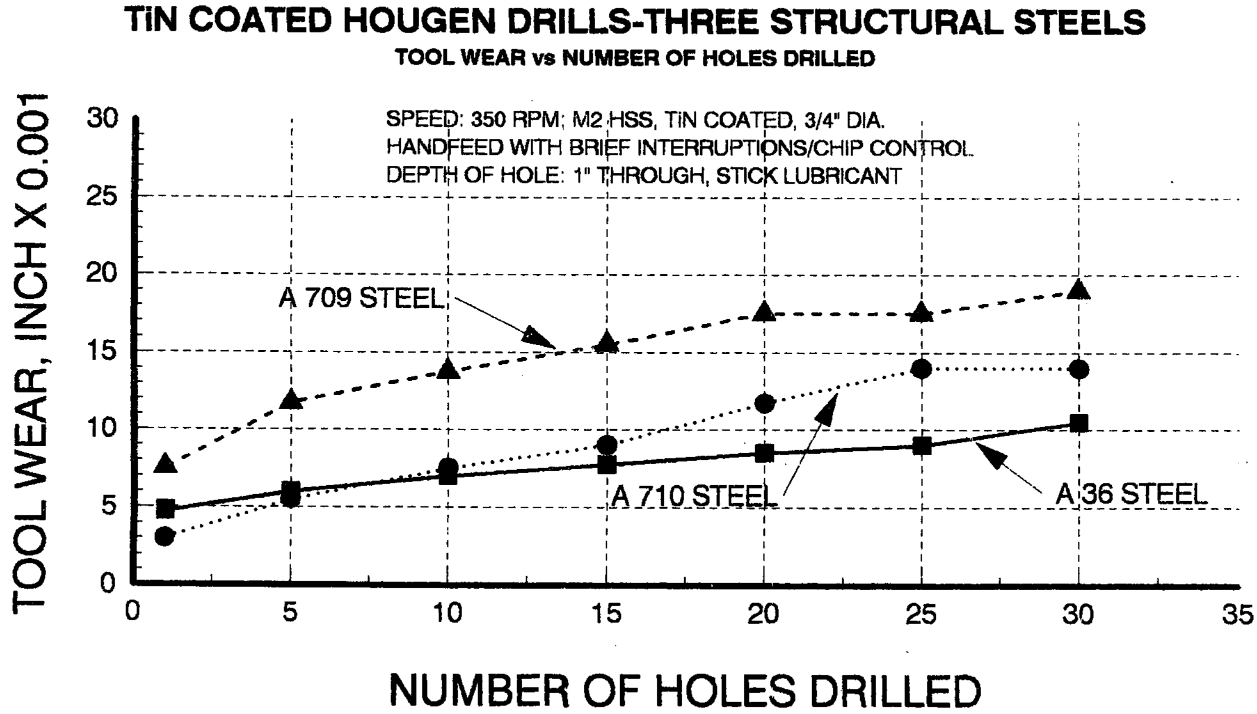


*Figure 62.* The comparison of the tool wear obtained on all three structural steels, using the titanium nitride (TiN) coated Hougen Rotabroach™ drills. The A36 steel, the softest of the three materials, produced the lowest tool wear. The A710 steel resulted in approximately 0.005 inch less tool wear than the A709 steel.

There are two techniques to minimize or eliminate BUE. One can either use a higher cutting speed or use a better lubricant. Using a higher speed would necessitate a different (better hot-hardness) tool material such as tungsten or cobalt carbide. The previously cited holes were drilled essentially dry, since the paste lubricant disappears after the entrance of the cutter past the surface of the hole. Any good cutting fluid, applied successfully to the cutting surfaces of the drill generally results in significant improvement in hole finish.

### *B. Carbide-Tipped Drills*

Additional drilling work was performed using carbide-tipped annular cutters manufactured by the Hougen Co. These cutters were used at the speed of 350 rpm, which was recommended by the manufacturer. The A36, the A709, and the A710 steels were drilled with these carbide-tipped drills. Although the ¾ inch diameter size cutters were not available in carbide-tipped, the next closest size available was 9/16 inch diameter and was purchased.

Five preliminary holes were successfully drilled in the softer (156 BHN) A36 steel. After the fifth hole, there was an average tool wear of 0.003 inch over the 4 teeth with very light edge chipping. One hole was drilled in the A709 steel at 229 BHN. There was an average tool wear of 0.005 inch on three teeth with the fourth tooth badly chipped. This cutter was presumed to have failed. One hole was also drilled in the A710 steel at 229 BHN. The results were similar to those of the A709 steel. The average tool wear on three teeth was only 0.002 inch with one tooth severely chipped. This cutter was also considered as unfit for drilling additional holes.

These test results confirmed suspicions about the type of carbide used to tip these cutters. An inquiry was made to the technical support personnel at the Hougen headquarters about the carbide-tipped cutters before ordering additional bits.

Hougen confirmed that the carbide was a C-2, which is a grade of tungsten carbide and cobalt binder, used for general purpose wear resistance for machining gray cast iron and many non-ferrous materials. C-2 has a transverse rupture strength of less than 300 ksi. Transverse rupture strength has good correlation with edge toughness in a cutting tool. It was determined that a micro-grain carbide would be more appropriate, since it has a much finer grain size and contains almost twice as much cobalt binder, resulting in a transverse rupture strength of almost 500 ksi. Although the wear resistance of micro-grain carbide is less than that of the C-2 carbide, typically edge chipping is eliminated, permitting more regrinds on the used tools.

The following surface roughness readings were taken on the holes drilled with the C-2 carbide-tipped drills. For A36 steel, the average roughness reading for the five holes was 224 μin, with a range of readings from 181 to 250 μin. The primary reason for the higher readings is the built-up-edge on the hole walls due to the relative softness of A36 steel at 156 BHN.

For A709 and A710 steels, only one hole was drilled in each of these steels due to serious chipping of the carbide tips of each cutter after one hole. The surface roughness reading on the A709 hole was 170 μin, and the reading on the A710 steel was 174 μin, a very similar value. Both of these steels exhibited built-up-edge (BUE) on the hole walls.

### *C. Titanium Nitride Coatings*

Additional holes were drilled in the three steels with annular cutters, this time using titanium nitride (TiN) coated M-2 high speed steel cutters. These cutters were manufactured by G & J Hall of Sheffield, England, and marketed by the Travers Tool Co., Inc., headquartered in Flushing, NY. These cutters were used at the speed of 350 rpm, which was the same speed as in the previous drilling tests. The A36, the A709, and the A710 steels were drilled with these TiN coated drills of ¾ inch diameter size.

The TiN coated drills were examined with a microscope before drilling any holes. The grind on these cutters before coating was very ragged with the intersections somewhat rounded by poor grinding. The results of these tests were disappointing as expected, based on the condition of the teeth, negating any potentially beneficial effect of the TiN coating on the performance of these drills. In each test the cutter became so dull that it stalled the spindle before completing the hole.

Four holes were drilled in the A36 steel with stalling on the fifth hole. Six holes were drilled in the A709 steel with stalling on the seventh hole. When drilling the A710 steel, the cutter stalled on the first hole and could not be extracted from the hole. These results confirm the inferior quality of these cutters, and they were declared as unsuitable for drilling holes in steel.

A final drilling sequence was begun using Hougen Rotabroach cutters, coated with titanium nitride (TiN). These cutters obtained from Hougen were coated by Balzars, a domestic coating source. The grinding on these cutters were substantially better, and their quality was reflected by their improved performance.

### *D. Tool Wear*

In *Figures 63 to 65,* tool wear on the coated drills is compared with the tool wear on the uncoated drills. *Figure 63* is a comparison of the tool wear of the TiN coated drill with the uncoated drill on A36 steel. The uncoated drill permitted twice the number of holes drilled at 0.005 inch less tool wear. *Figure 64* shows the comparison of the coated drill with the uncoated drill on the A709 steel. The tool life was extended from 13 holes to 30 holes drilled with the TiN coated drills. The TiN coated drill extended the tool life to 30 holes, compared to 15 holes with the uncoated drill on the A710 steel in *Figure 65.*

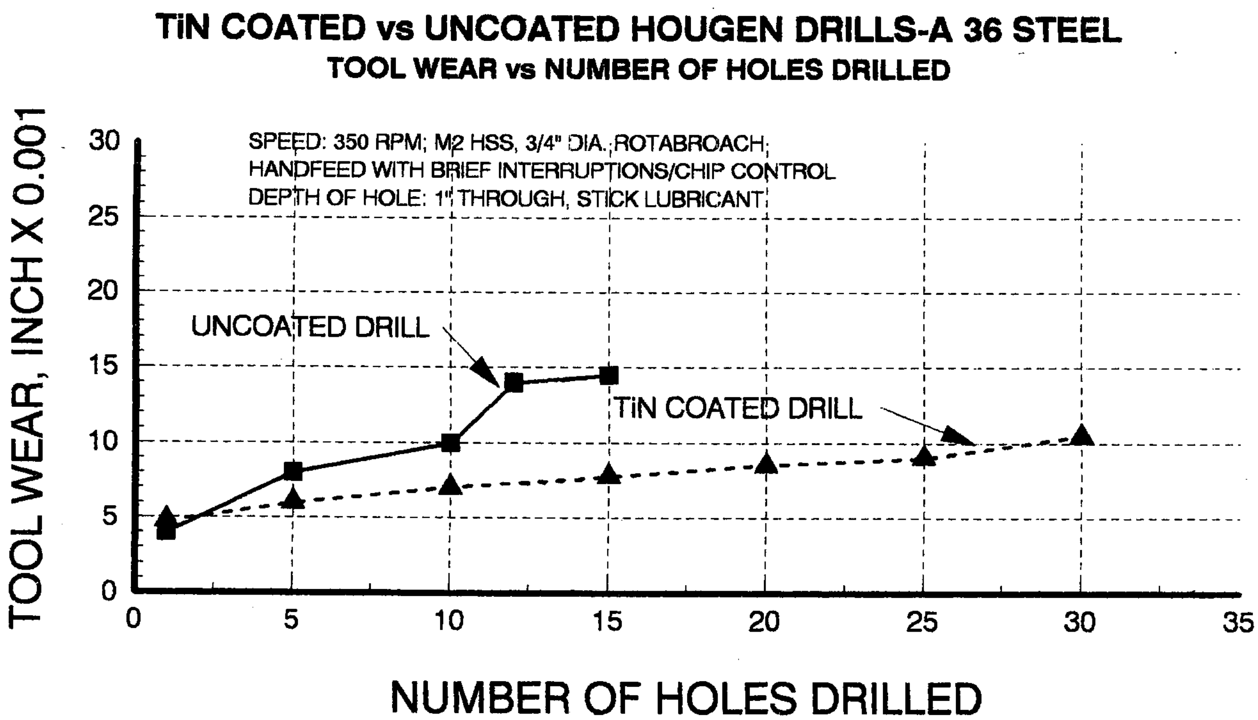


*Figure 63.* The comparison of the durability of ¾" diameter uncoated M2 high speed Hougen drills vs. the same drills coated with titanium nitride (TiN) when drilling A36 steel. The uncoated drills had equivalent performance only up to about 10 holes drilled, compared to the TiN coated drills that had the same wear even after drilling triple the number of holes.

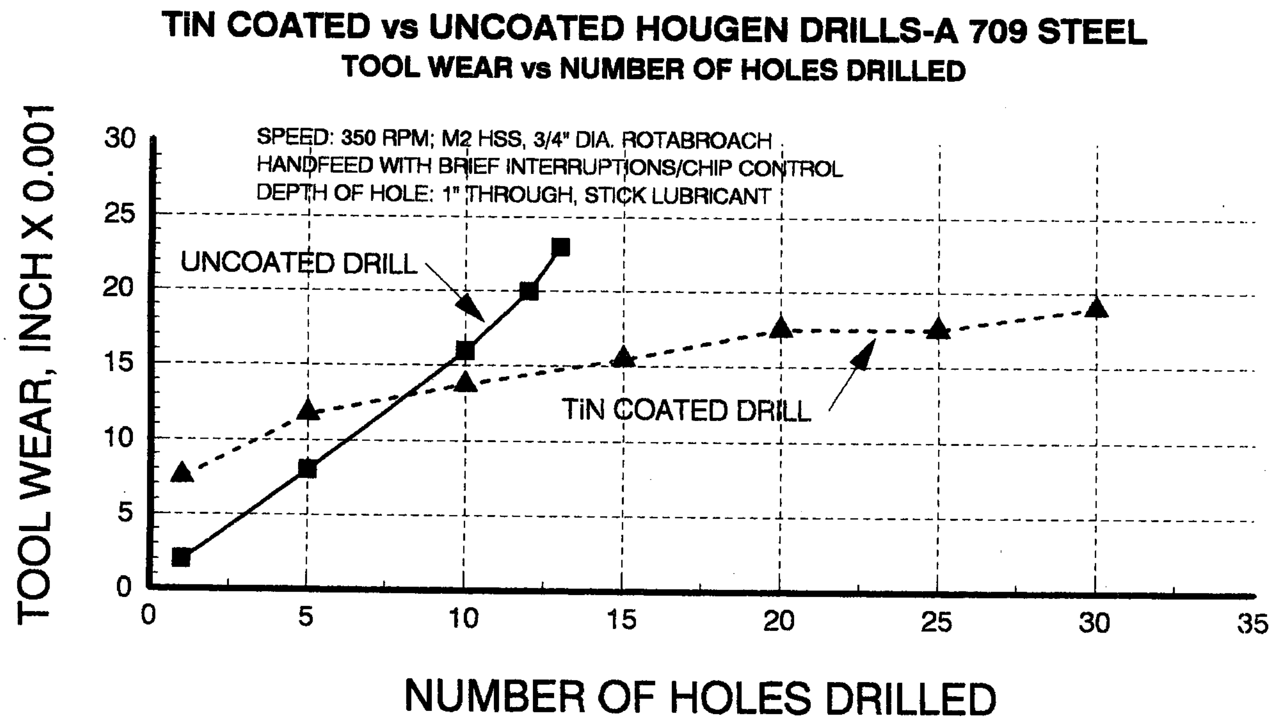


*Figure 64.* The comparison of the durability of ¾ inch diameter uncoated M2 high speed Hougen drills vs. the same drills coated with titanium nitride (TiN) when drilling A709 HPS 70W steel. The uncoated drills had equivalent performance only up to about 12 holes drilled, compared to the TiN coated drills that had the same wear even after drilling nearly triple the number of holes. After drilling 30 holes in the A709 steel, the TiN coated drill had sustained twice the wear compared to A36 steel.

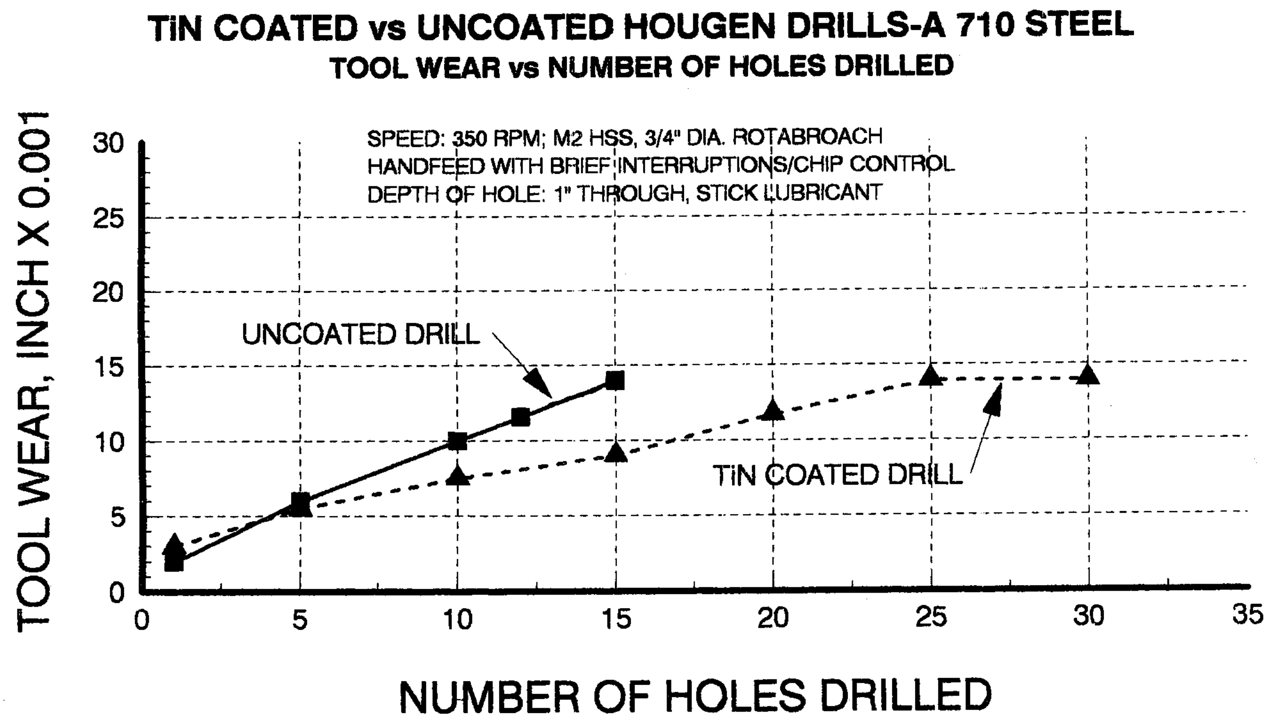


*Figure 65.* The comparison of the durability of uncoated M2 high speed Hougen drills vs. the same drills coated with titanium nitride (TiN) when drilling A710 Grade B HP steel. The uncoated drills had equivalent performance only up to about 15 holes drilled, compared to the TiN coated drills that had the same wear even after drilling double the number of holes. After drilling 30 holes in the A709 steel, the TiN coated drill had sustained about 1.5 times the wear compared to A36 steel.

### *E. Surface Roughness*

*Figures 66 and 67* compare the surface roughness of the holes produced by the coated Hougen drills with the roughness of the holes produced by the uncoated Hougen drills.

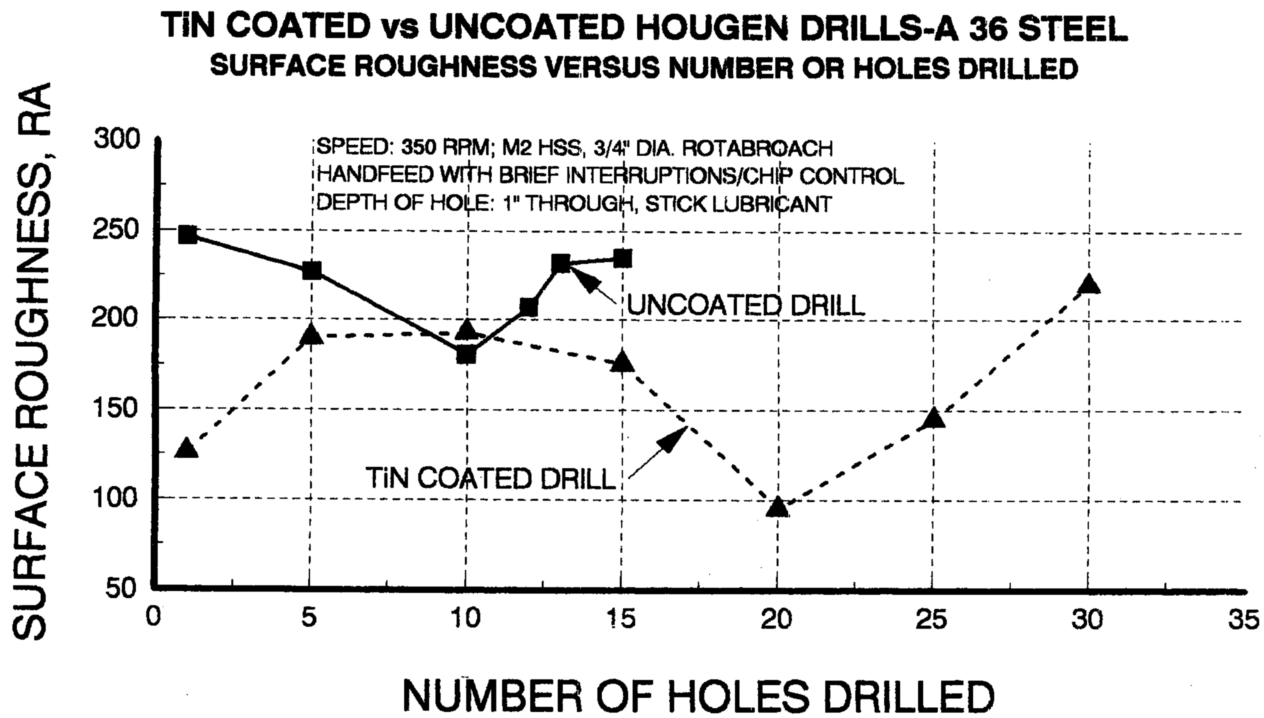


*Figure 66.* The surface of the inside diameter of holes drilled in A36 steel vs. the number of holes drilled with ¾" diameter M2 high speed steel (HSS) annular drills that were uncoated or coated with titanium nitride (TiN). In both cases, there is an improvement of the surface roughness after drilling a number of holes. When drilling A36 with uncoated HSS, this occurred after 10 holes were drilled, gradually decreasing from 250 μin to 200 μin. For the TiN coated drills, this decrease was from 200 μin to 100 μin. Presumably this phenomenon is attributed to a wear-in process that improves the edge profile of the cutting edges, until a portion of the HSS or the TiN is abraded away, and roughness begins to increase again.

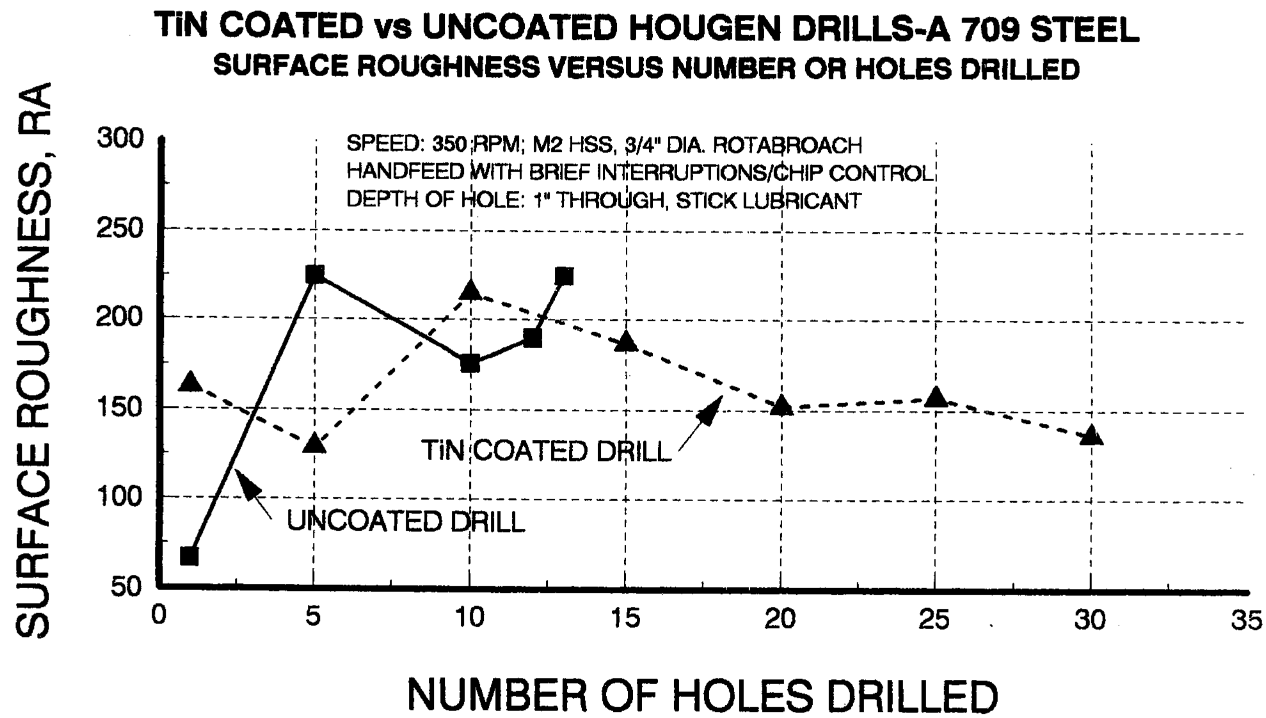


*Figure 67.* The inside surface of holes drilled in A709 steel vs. the number of holes drilled with ¾ inch diameter M2 HSS annular drills that were uncoated or coated with titanium nitride (TiN). In both cases, there is an improvement of the surface roughness after drilling a number of holes, although the improvement is minimal with the uncoated drills. However, when drilling A709 with uncoated HSS, after 5 holes were drilled, there was a gradually decrease from 225 µin to 175 µin, but rapidly increased again. For the TiN coated drills, this decrease after 10 holes were drilled was from 220 µin to 190 µin, with no apparent increase. The wear-in process previously described in *Figure 66* that improves the edge profile of the cutting edges as portions of the TiN are abraded away is apparently delayed for a longer period in A709 steel compared to drilling the A36 steel.

### *F. High Speed Steel Twist Drills*

Twist drills are commonly used for hole drilling, even though annular cutters are more energy efficient. Larger diameter drills are hollowed at the tip to allow for cutting fluid flow. In this study, the twist drills received an ample spray of cutting fluid, similar to flooded drills.

*Figure 68* is a plot of the number of holes drilled to 1 inch depth with ¾ inch high speed steel twist drills vs. their cutting speed for the three steels. The A36 has similar behavior to the HP steels in the range 80-110 fpm. The number of holes drilled in HP steels is equivalent or better than the softer A36, particularly at lower cutting speeds.

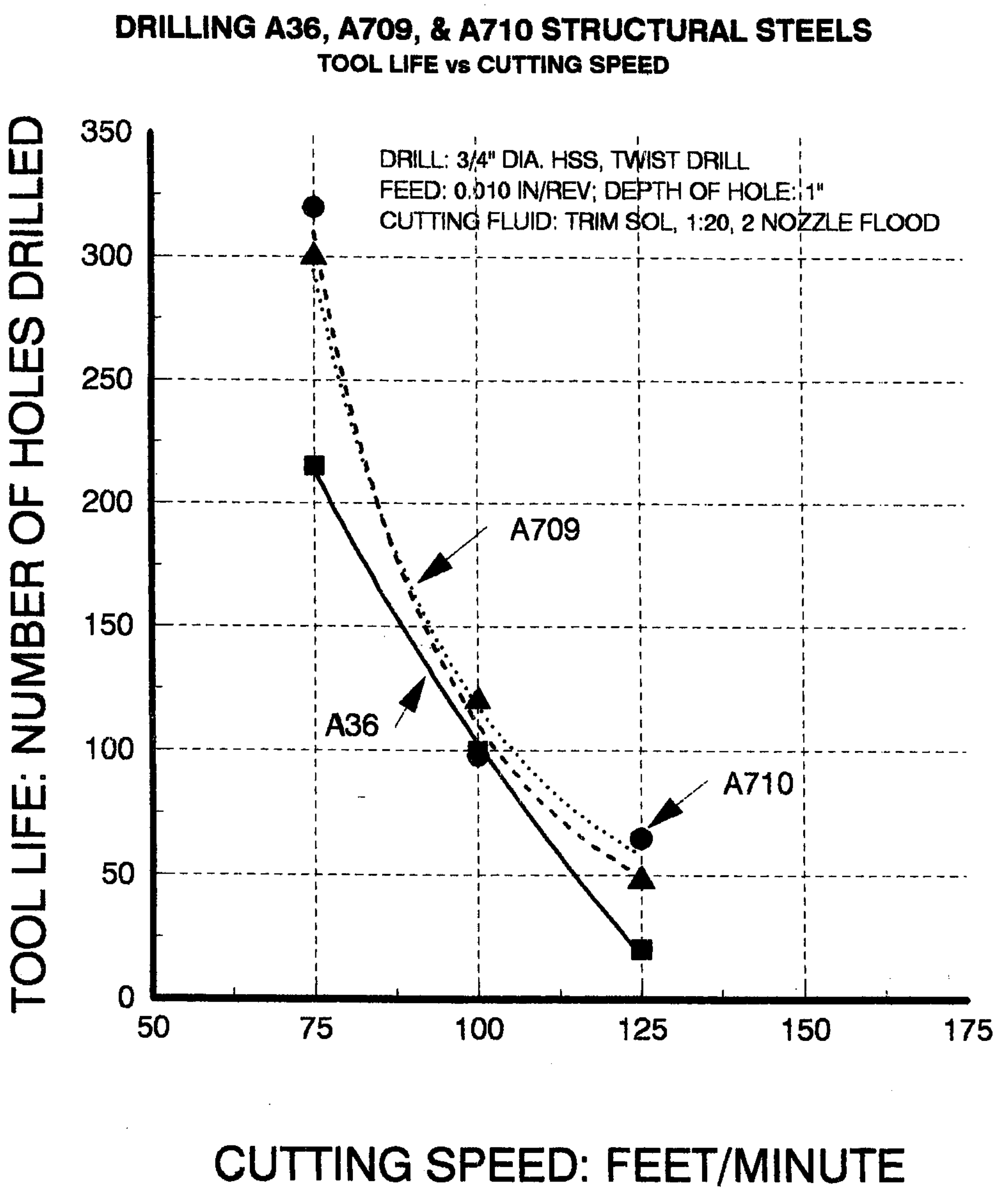


*Figure 68* shows the effect of changing cutting speed for ¾ inch diameter high speed steel twist drills at a feed rate of 0.010 inch per revolution on tool life as a function of the number of holes drilled. A36 has similar attributes to the HP steels, but more holes were drilled with the HP steels due to better break up of chips in the flutes and reduced the galling associated with the softer ferrite of the A36 steel.

## 9. GENERAL SUMMARY

This report compared the machining characteristics of three structural steels, including ASTM A36 structural steel, ASTM A709 HP 70W and A710 Grade B high performance (HP) steels by sawing, cutting, milling, grinding and drilling each steel. Based on all of the tests conducted in this investigation, the two HP steels have a machinability equivalent or better than conventional ASTM A36 structural steel. Detailed evaluations included measuring surface roughness of each steel after machining, the tool wear of the cutters used, and the amount of metal removed by saw blades, grinding wheels, face and end mill cutters, annular drills and high speed steel twist drills.

The general parameters to obtain certain end results by machining these steels by the various processes of cutting, sawing, milling, grinding and drilling are summarized in *Text Table 5.* All dimensions are in inches, except as noted.

The surface roughness of the A36 carbon steel was slightly higher than the HP steel. This difference was apparently due to its larger grain size, numerous pearlite islands and prominent banding in a soft ferrite matrix. In contrast, the HP steels had much lower carbon content, fine grain size and harder ferrite matrix due to higher alloy content, with a fine dispersion of hardened intermetallic precipitates. This uniformity provided a smoother surface when milled or ground.

Although ASTM A588 and A572 structural plate steels were not evaluated in this study due to cost constraints, it is anticipated that machining these steels would have a machinability similar to the HP steels if they have fine grain sizes, minimal banding of pearlite, and have carbon contents of 0.15% or less. Although turning and tapping were not part of this investigation, based on results of this work, the machinability of the HP steels is estimated to be 50-60% of SAE 1212 at 100%.

A wide variety of carbon and alloy steels are used in the construction industry for structures, machinery, bridges and road construction. *Text Table 6* is a list of common steels, their typical applications, and range of machinability of primarily obtained from turning of bars as compared to free-machining SAE 1212 steel bars with a machinability rating of 100%. Because machinability is measured by various methods, a range is presented, based on data obtained from authoritative sources.

*Text Table 5* / MACHINING PROCESS PARAMETER SUMMARY for A36, A709 HPS 70W and A710 GRADE B STEELS

| *Process* | *Characteristic* | *A36* | *A709 HPS 70W* | *A710 Grade B* |
|---|---|---|---|---|
| Saw Cutting | Saw wear | 0.028 | 0.005 | 0.022 |
| | Tool material | M42 HSS | M42 HSS | M42 HSS |
| | Speed range | 120 fpm | 120 fpm | 120 fpm |
| | Material sawed to 0.020 wear | 260 $in^2$ | 320 $in^2$ | 410 $in^2$ |
| | Cutting fluid | Heavy duty mineral oil | Heavy duty mineral oil | Heavy duty mineral oil |
| Grinding | Surface Roughness Parallel to lay | 4-6 µin | 4-9 µin | 4-6 µin |
| | Down feed | 0.0005 / 0.0015 | 0.0015 / 0.0010 | 0.0005-0.0010 |
| | Cross feed | 0.030 / 0.130 | 0.030 / 0.130 | 0.030 |
| | Surface Roughness Perpendicular to lay | 8-15 µin | 19-22 µin | 11-16 µin |
| | Down feed | 0.001 | 0.0015-0.0020 | 0.0005-0.0010 |
| | Cross feed | 0.030 | 0.030 | 0.030 |
| Drilling, annular drills | Number of holes drilled at 0.015 inch wear, M2 HSS | 15 | 10 | 15 |
| | Number of holes drilled at 0.015 inch wear, TiN HSS | 30 | 15 | 30 |
| | Inside surface roughness after 15 holes drilled, M2 HSS | 235 | 225 | NDA |
| | Inside surface roughness after 15 holes drilled, TiN HSS | 175 | 180 | NDA |
| Drilling, twist drills | Number of holes with ¾ inch HSS at 0.010 inch feed / rev at 75 fpm | 210 | 320 | 300 |

NDA = no data available

*Text Table 5* / MACHINING PROCESS PARAMETER SUMMARY forA36, A709 HPS 70W and A710 GRADE B STEELS

| *Process* | *Characteristic* | *A36* | *A709 HPS 70W* | *A710 Grade B* |
|---|---|---|---|---|
| Face Milling | Surface Roughness, avg | 20 μin | 15 μin | 15μin |
| | Feed rate, ipt | 0.005-0.009 | 0.003-0.007 | 0.005-0.007 |
| | Cutting speed | 900 fpm | 500-700 | 700-900 |
| | HSS tool wear after 20 min | 0.007 | 0.018 | 0.015 |
| End Milling | Surface roughness after 20 min, ½ inch Ø M2 HSS | 160 μin | 65 μin | 50 μin |
| | Surface roughness after 20 min, ¾ inch Ø M2 HSS | 50 μin | 45 μin | 45 μin |
| | Tool wear after 20 minutes, M2 HSS | 0.013 | 0.008 | 0.008 |
| | Tool wear after 20 minutes, M42 HSS | 0.009 | 0.007 | 0.007 |
| | Tool wear after 20 minutes, TiN HSS | 0.009 | 0.008 | 0.007 |
| | Tool wear after 20 minutes, ½ inch Ø M2 HSS | 0.018 | 0.008 | 0.008 |
| | Tool wear after 20 minutes, ¾ inch Ø M2 HSS | 0.018 | 0.008 | 0.012 |
| | Cutting time, 3 flute HSS, min | 18 | 24 | 29 |
| | Cutting time, 4 flute HSS, min | 22 | 37 | 41 |
| | Metal removed, ¾ inch Ø M2 HSS | 29 $in^3$ | 41 $in^3$ | 45 $in^3$ |

*Text Table 6* / MACHINABILITY OF COMMON STEELS USED IN CONSTRUCTION

| *Alloy* | *BHN* | *Typical Applications* | *Machinability** |
|---|---|---|---|
| SAE 1212 | 165 | Free machining reference steel | 100% |
| SAE 12L14 | 165 | Shafting and rods for precision work | 160-180% |
| ASTM A36 | 150-162 | Structural shapes, bars, flats | 45-50% |
| SAE 1018 hot rolled | 116 | General purpose weldable steel for round bars, plates and sheets | 52% |
| SAE 1018 cold drawn | 126 | General purpose steel for machine work requiring better machinability than 1018 HR | 70% |
| ASTM A706 Grade 60 | 165 | Weldable reinforcing bars, dowels, and anchor bolts | 55-60% |
| ASTM A615 Grade 60 | 162 | Non-weldable reinforcing bars | 56% |
| SAE 8620 hot rolled | 185-194 | Tough steel for round bars, plates; can be carburized for wear resistance | 60% |
| SAE 4140 hot rolled | 190 | Heavy duty shafting subject to moderate cyclic stresses | 55-57% |
| SAE 4140 quenched & tempered | 255-302 | Heavy duty shafting subject to higher stresses; ASTM F1554 Grade 105 anchor bolts | 55% |
| ASTM A193 Grade B7 | 269-321 | A325 and A490 bolts and nuts; heavy duty thread stock | 38% |
| SAE 4340 quenched & tempered | 302-363 | For large diameter heavy duty shafting subject to high cyclic stresses; large diameter hardened bolts and nuts | 32% |
| ASTM A514 quenched & tempered | 235-293 | For plate steels subjected to higher cyclic stress for bridges and structures; weldable; plow and grader blades | 25% |
| SAE 4130 hot rolled | 187-229 | For intermediate size shafting; hardenable by quenching; available in aircraft quality | 70% |
| SAE 4150 quenched & tempered | 209-320 | For very large diameter shafting capable of sustaining high stresses; hardened large diameter bolt and nuts | 43% |
| ASTM A588 Grade 50 | 156 | Weathering steel plates and sheet for bridges and structural shapes | 50-55%** |
| ASTM A572 Grade 50 | 156 | Plate steel for bridges and structures; typically has good toughness | 50-55%** |
| ASTM A709 HPS 70W | 229 | Plate steel for bridges and structures; high toughness & weathering similar to A588 | 50-60%** |
| ASTM A710 Grade B | 229 | Plate steel for bridges and structures; high toughness & weathering better than A588 | 50-60** |

*Ratings are derived from several reliable data sources, which use multiple indicators for their determination. Reliable data sources for the above table include Ryerson Steel (Ref J), the Carboloy Division of General Electric (Ref H), Avondale Industries (Ref I), and the Society of Manufacturing Engineers (Ref H). Values for A588 and A572 are estimates based on machining data obtained from this investigation.

**Machinability ratings are based on the use of high speed steel cutters, and ratings should be treated only as reliable estimates.

## 10. REFERENCES

A. E. Oberg, F. Jones, H. Horton and H. Ryffell, *Machinery's Handbook, 26th Edition,* Industrial Press, New York, 2000.

B. *Machining Data Handbook, Third Edition*, Institute of Advanced Manufacturing Sciences, Cincinnati, OH, Jan 1980.

C. G. Bellows, *Low Stress Machining for Quality Production,* Machinability Data Center, Cincinnati, OH, Aug 1978.

*D. Metals Handbook, Vol. 1, Irons, Steels and High Performance Alloys,* ASM International, Metals Park, OH, 1990.

E. *Trim Sol General Purpose Emulsion Data & Information*, Master Chemical Corp, Perrysburg, OH, Dec 2009

F. *Material Safety Data Sheet, Lenox Saw Master Synthetic Fluid,* American Saw & Manufacturing Co., East Longmeadow, MA, 23 Jan 2002.

G. *Hougen Technical Support Web Site/Tech Tips/Cutter Information,* Hougen Manufacturing Co., Swartz Creek, MI, Jan 2011.

H. *Tool and Manufacturing Engineers Handbook, Vol 1, Machining,* 4th Edition, Society of Manufacturing Engineers, Dearborn, MI, 1983.

I. *Alloy Color Codes and Machinability,* Danly Machine Div, Avondale Industries, Chicago, 1986.

J. Mechanical Properties of Steel, *Ryerson Stock List,* Ryerson, Inc., 2007.

K. E. DeGarmo, *Materials and Processes in Manufacturing, Third Edition*, McMillan, London. 1970.

## APPENDIX

*Data Table 1* / FACE MILLING A36, A709 HPS 70W and A710 GRADE B HP STEELS

Effect of Cutting Speed and Feed on Surface Roughness, $R_A$

Cutter: 4 inch Dia. 5 Tooth Face Mill, using only one insert
Tool Material: Mitsubishi, TiN Coated Carbide SNMG-433 Insert
Axial Depth of Cut: 0.050 inch
Radial Depth of Cut: 2.0 inches (width of work piece)
Cutting Fluid: Dry, no fluid
Setup: Down milling, centerline offset: 1.1 inch

| Cutting Speed, ft/min | Feed, in./tooth | Surface Roughness, $R_A$ |
|---|---|---|
| | A36 Steel | |
| 300 | 0.005 | 84 |
| 500 | 0.005 | 28 |
| 700 | 0.005 | 51 |
| 900 | 0.005 | 20 |
| 500 | 0.003 | 61 |
| 500 | 0.007 | 55 |
| 500 | 0.009 | 68 |
| 900 | 0.007 | 19 |
| 900 | 0.009 | 23 |
| 900 | 0.011 | 42 |
| | A709 Steel | |
| 300 | 0.005 | 26 |
| 500 | 0.005 | 14 |
| 700 | 0.005 | 18 |
| 900 | 0.005 | 24 |
| 500 | 0.003 | 11 |
| 500 | 0.007 | 14 |
| 500 | 0.009 | 26 |
| 900 | 0.007 | 33 |
| 900 | 0.009 | 43 |
| 900 | 0.011 | 55 |
| | A710 Steel | |
| 300 | 0.005 | 21 |
| 500 | 0.005 | 22 |
| 700 | 0.005 | 7 |
| 900 | 0.005 | 8 |
| 500 | 0.003 | 11 |
| 500 | 0.007 | 7 |
| 500 | 0.009 | 16 |
| 900 | 0.007 | 8 |
| 900 | 0.009 | 14 |
| 900 | 0.011 | 24 |

## *Data Table 2* / FACE MILLING A36, A709 AND A710 STEELS

### Effect of Cutting Time on Tool Wear and Surface Roughness, $R_A$

Cutter: 4 inch Dia. 5 Tooth Face Mill, using only one insert
Tool Material: Mitsubishi US735, TiN Coated Carbide SNMG-433 Insert
Cutting Speed: 1500 ft/min.
Axial DOC: 0.050 inch; Radial DOC: 2.0 inch
Cutting Fluid: Dry, no fluid
Setup: Down milling, centerline offset: 1.1 inch

| Cutting Time, min | Tool Wear, inch | Surface Roughness, $R_A$ |
|---|---|---|
| | A36 Steel | |
| 1.2 | 0.001 | 49 |
| 3.6 | 0.003 | 51 |
| 6.0 | 0.004 | 54 |
| 0.5 | 0.004 | 56 |
| 10.9 | 0.005 | 56 |
| 13.3 | 0.005 | 56 |
| 15.7 | 0.005 | 51 |
| 18.1 | 0.006 | 51 |
| 20.6 | 0.008 | 51 |
| 23.0 | 0.008 | 54 |
| 25.4 | 0.016 | 55 |
| | A709 Steel | |
| 1.2 | 0.001 | 20 |
| 3.6 | 0.002 | 17 |
| 6.0 | 0.003 | 14 |
| 0.5 | 0.004 | 11 |
| 10.9 | 0.005 | 16 |
| 13.3 | 0.006 | 16 |
| 15.7 | 0.008 | 16 |
| 18.1 | 0.012 | 25 |
| 20.6 | 0.017 | 69 |
| | A710 Steel | |
| 1.2 | 0.002 | 26 |
| 3.6 | 0.004 | 26 |
| 6.0 | 0.005 | 26 |
| 0.5 | 0.005 | 25 |
| 10.9 | 0.006 | 25 |
| 13.3 | 0.007 | 25 |
| 15.7 | 0.008 | 37 |
| 18.1 | 0.010 | 97 |
| 20.6 | 0.015 | 97 |

## *Data Table 3* / END MILLING A36 STEEL AT156 BHN

### Effect of Cutting Time and Tool Wear on Surface Roughness, $R_A$

Cutter: Putnam Brand ½ inch Dia., HSS 4 Flute End Mill-See Below
Feed Rate: 0.002 ipt
Axial Depth of Cut: 0.050 inch (1 Dia.)
Radial Depth of Cut: 0.125 inch (Dia./4)
Cutting Fluid: Trim Sol, 1:20
Setup of Cutter to Work piece: Down milling

| Corner Wear, inch | Cutting Time, min. | Surface Roughness, $R_A$ |
|---|---|---|
| | M2 High Speed Steel End Mills | |
| 0.002 | 1.96 | 67 |
| 0.004 | 5.88 | 56 |
| 0.010 | 9.81 | 82 |
| 0.010 | 13.74 | 113 |
| 0.012 | 17.66 | 164 |
| 0.014 | 21.59 | 154 |
| cutter broke | 22.91 | .... |
| | M42 High Speed Steel End Mills | |
| 0.003 | 1.96 | 79 |
| 0.005 | 5.88 | 93 |
| 0.006 | 9.81 | 112 |
| 0.008 | 13.74 | 93 |
| 0.008 | 17.66 | 93 |
| 0.010 | 21.59 | 73 |
| 0.010 | 25.52 | 83 |
| 0.012 | 29.44 | 83 |
| 0.016 | 33.37 | 100 |
| | TiN Coated High Speed Steel End Mills | |
| 0.002 | 1.96 | 48 |
| 0.004 | 5.88 | 73 |
| 0.005 | 9.81 | 74 |
| 0.006 | 13.74 | 76 |
| 0.007 | 17.66 | 76 |
| 0.008 | 21.59 | 97 |
| 0.010 | 25.52 | 135 |
| 0.011 | 29.44 | 120 |
| 0.012 | 33.37 | 139 |
| cutter broke | 33.55 | .... |

## *Data Table 4* / END MILLING STRUCTURAL STEELS USING 3 FLUTE END MILLS

### Effect of Cutting Time and Tool Wear on Surface Roughness, $R_A$

Cutter: Putnam Brand ½ inch Dia., M2 HSS 3 Flute End Mill
Feed Rate: 0.002 ipt
Axial Depth of Cut: 0.050 inch (1 Dia.)
Radial Depth of Cut: 0.125 inch (Dia./4)
Cutting Fluid: Trim Sol, 1:20
Setup of Cutter to Work piece: Down milling

| Corner Wear, inch | Cutting Time, min. | Surface Roughness, $R_A$ |
|---|---|---|
| | A36 Steel | |
| 0.004 | 2.62 | 62 |
| 0.006 | 7.86 | 82 |
| 0.012 | 13.10 | 117 |
| 0.016 | 18.34 | 161 |
| | A709 Steel | |
| 0.006 | 2.62 | 32 |
| 0.008 | 7.86 | 50 |
| 0.010 | 13.10 | 64 |
| 0.011 | 18.34 | 24 |
| 0.012 | 23.58 | 64 |
| | A710 Steel | |
| 0.004 | 2.62 | 28 |
| 0.005 | 7.86 | 33 |
| 0.007 | 13.10 | 45 |
| 0.009 | 18.34 | 39 |
| 0.010 | 23.58 | 59 |
| 0.012 | 28.82 | 73 |

## *Data Table 5* / END MILLING A36 STEEL USING IMPORTED END MILLS

### Effect of Cutting Time and Tool Wear on Surface Roughness, $R_A$

Cutter: Imported ½ inch Dia., HSS 4 Flute End Mill-See Below
Feed Rate: 0.002 ipt
Axial Depth of Cut: 0.050 inch (1 Dia.)
Radial Depth of Cut: 0.125 inch (Dia./4)
Cutting Fluid: Trim Sol, 1:20
Setup of Cutter to Work piece: Down milling

M2 High Speed Steel End Mills

| Corner Wear, inch | Cutting Time, min. | Surface Roughness, $R_A$ |
|---|---|---|
| 0.004 | 1.96 | 79 |
| 0.004 | 3.92 | 67 |
| 0.008 | 5.89 | 104 |
| 0.009 | 7.85 | 90 |
| 0.010 | 9.81 | 100 |
| 0.010 | 11.78 | 106 |
| 0.010 | 13.74 | 126 |
| 0.012 | 17.66 | 96 |

M42 High Speed Steel End Mills

| Corner Wear, inch | Cutting Time, min. | Surface Roughness, $R_A$ |
|---|---|---|
| 0.002 | 1.96 | 48 |
| 0.004 | 5.88 | 73 |
| 0.005 | 9.81 | 74 |
| 0.006 | 13.74 | 76 |
| 0.007 | 17.66 | 76 |
| 0.008 | 21.59 | 97 |
| 0.010 | 25.52 | 135 |
| 0.011 | 29.44 | 120 |
| 0.012 | 33.37 | 139 |

## *Data Table 6* / END MILLING A709 HPS 70W STEEL, 229 BHN

### Effect of Cutting Time and Tool Wear on Surface Roughness, $R_A$

Cutter: Putnam Brand ½ inch Dia., HSS 4 Flute End Mill-See Below
Feed Rate: 0.002 ipt
Axial Depth of Cut: 0.050 inch (1 Dia.)
Radial Depth of Cut: 0.125 inch (Dia./4)
Cutting Fluid: Trim Sol, 1:20
Setup of Cutter to Work piece: Down milling

| Corner Wear, inch | Cutting Time, min. | Surface Roughness, $R_A$ |
|---|---|---|
| | M2 HSS End Mills | |
| 0.004 | 1.96 | 19 |
| 0.005 | 5.88 | 56 |
| 0.016 | 9.81 | 65 |
| 0.008 | 13.74 | 79 |
| 0.008 | 17.66 | 60 |
| 0.008 | 21.59 | 73 |
| 0.009 | 25.52 | 48 |
| 0.009 | 29.44 | 54 |
| 0.010 | 33.37 | 53 |
| 0.012 cutter broke | 37.30 | 66 |
| | M42 HSS End Mills | |
| 0.003 | 1.96 | 47 |
| 0.005 | 5.88 | 35 |
| 0.006 | 9.81 | 44 |
| 0.006 | 13.74 | 60 |
| 0.007 | 17.66 | 65 |
| 0.008 | 21.59 | 65 |
| 0.009 cutter broke | 25.52 | 75 |
| | TiN Coated HSS End Mills | |
| 0.004 | 1.96 | 25 |
| 0.006 | 5.88 | 36 |
| 0.007 | 9.81 | 41 |
| 0.008 | 13.74 | 61 |
| 0.008 | 17.66 | 67 |
| 0.009 | 21.59 | 39 |
| 0.009 | 25.52 | 72 |
| 0.009 | 29.44 | 80 |
| 0.010 | 33.37 | 83 |
| 0.0105 | 37.30 | 46 |
| 0.011 | 41.23 | 84 |
| 0.011 | 45.15 | 97 |
| 0.012 | 49.08 | 65 |

*Data Table 7* / END MILLING A710 GRADE B STEEL, 229 BHN

Effect of Cutting Time and Tool Wear on Surface Roughness, $R_A$

Cutter: Putnam Brand ½ inch Dia., HSS 4 Flute End Mill-See Below
Feed Rate: 0.002 ipt
Axial Depth of Cut: 0.050 inch (1 Dia.)
Radial Depth of Cut: 0.125 inch (Dia./4)
Cutting Fluid: Trim Sol, 1:20
Setup of Cutter to Work piece: Down milling

| Corner Wear, inch | Cutting Time, min. | Surface Roughness, $R_A$ |
|---|---|---|
| | **M2 High Speed Steel End Mills** | |
| 0.003 | 1.96 | 23 |
| 0.004 | 5.88 | 33 |
| 0.015 | 9.81 | 55 |
| 0.006 | 13.74 | 42 |
| 0.007 | 17.66 | 62 |
| 0.009 | 21.59 | 42 |
| 0.010 | 25.52 | 35 |
| 0.010 | 29.44 | 43 |
| 0.010 | 33.37 | 63 |
| 0.011 | 37.30 | 83 |
| 0.012 | 41.23 | 65 |
| | **M42 High Speed Steel End Mills** | |
| 0.004 | 1.96 | 33 |
| 0.005 | 5.88 | 53 |
| 0.006 | 9.81 | 47 |
| 0.006 | 13.74 | 59 |
| 0.006 | 17.66 | 73 |
| 0.008 | 21.59 | 68 |
| 0.008 | 25.52 | 56 |
| 0.010 | 29.44 | 45 |
| 0.011 | 33.37 | 52 |
| 0.011 | 37.30 | 86 |
| 0.012 | 41.23 | 61 |
| | **TiN Coated High Speed Steel End Mills** | |
| 0.004 | 1.96 | 25 |
| 0.004 | 5.88 | 36 |
| 0.005 | 9.81 | 41 |
| 0.005 | 13.74 | 61 |
| 0.006 | 17.66 | 67 |
| 0.008 | 21.59 | 39 |
| 0.009 | 25.52 | 72 |
| 0.009 | 29.44 | 80 |
| 0.010 | 33.37 | 83 |
| 0.011 | 37.30 | 46 |
| 0.012 | 41.23 | 84 |

## *Data Table 8* / END MILLING STRUCTURAL STEELS

### Effect of Cutting Time and Tool Wear on Surface Roughness, $R_A$

Cutter: Putnam Brand ¾ inch Dia., M2 HSS 4 Flute End Mill
Feed Rate: 0.004 ipt
Axial Depth of Cut: 0.750 inch (1 Dia.)
Radial Depth of Cut: 0.1875 inch (Dia./4)
Cutting Fluid: Trim Sol, 1:20
Setup of Cutter to Work piece: Down milling

A36 Steel

| Corner Wear, inch | Cutting Time, min. | Surface Roughness, $R_A$ |
|---|---|---|
| 0.003 | 1.47 | 45 |
| 0.007 | 4.42 | 62 |
| 0.008 | 7.36 | 62 |
| 0.010 | 10.31 | 69 |
| 0.010 | 13.25 | 84 |
| 0.010 | 16.20 | 55 |
| 0.013 | 19.14 | 49 |
| 0.014 | 22.09 | 67 |
| 0.016 | 25.03 | 91 |

A709 Steel

| Corner Wear, inch | Cutting Time, min. | Surface Roughness, $R_A$ |
|---|---|---|
| 0.004 | 1.47 | 35 |
| 0.005 | 4.42 | 52 |
| 0.006 | 7.36 | 44 |
| 0.007 | 10.31 | 54 |
| 0.008 | 13.25 | 51 |
| 0.008 | 16.20 | 43 |
| 0.008 | 19.14 | 44 |
| 0.008 | 22.09 | 43 |
| 0.009 | 25.03 | 46 |
| 0.010 | 27.98 | 36 |
| 0.012 | 30.92 | 42 |
| 0.015 | 33.87 | 66 |
| 0.016 | 36.81 | 45 |

## *Data Table 9* / END MILLING A710 STEEL

### Effect of Cutting Time and Tool Wear on Surface Roughness, $R_A$

Cutter: Putnam Brand ¾ inch Dia., 4 Flute End Mill, HSS-See Below
Feed Rate: 0.004 ipt
Axial Depth of Cut: 0.750 inch (1 Dia.)
Radial Depth of Cut: 0.1875 inch (Dia./4)
Cutting Fluid: Trim Sol, 1:20
Setup of Cutter to Work piece: Down milling

| Corner Wear, inch | Cutting Time, min. | Surface Roughness, $R_A$ |
|---|---|---|
| | M2 High Speed Steel | |
| 0.006 | 1.47 | 33 |
| 0.010 | 4.42 | 46 |
| 0.010 | 7.36 | 50 |
| 0.010 | 10.31 | 48 |
| 0.011 | 13.25 | 44 |
| 0.012 | 16.20 | 34 |
| 0.012 | 19.14 | 40 |
| 0.013 | 22.09 | 49 |
| 0.014 | 25.03 | 69 |
| 0.015 | 27.98 | 75 |
| 0.015 | 30.92 | 41 |
| 0.015 | 33.87 | 52 |
| 0.0155 | 36.81 | 48 |
| 0.018 | 39.80 | 57 |
| | M42 High Speed Steel | |
| 0.004 | 1.47 | 44 |
| 0.006 | 4.42 | 59 |
| 0.009 | 7.36 | 82 |
| 0.010 | 10.31 | 72 |
| 0.012 | 13.25 | 42 |
| 0.013 | 16.20 | 47 |
| 0.015 | 19.14 | 42 |
| 0.017 | 22.09 | 34 |

*Data Table 9* / END MILLING A710 STEEL

Effect of Cutting Time and Tool Wear on Surface Roughness, $R_A$

Cutter: Putnam Brand ¾ inch Dia., 4 Flute End Mill, HSS, Titanium Nitride Coated
Feed Rate: 0.004 ipt
Axial Depth of Cut: 0.750 inch (1 Dia.)
Radial Depth of Cut: 0.1875 inch (Dia./4)
Cutting Fluid: Trim Sol, 1:20
Setup of Cutter to Work piece: Down milling

TiN Coated High Speed Steel

| Corner Wear, inch | Cutting Time, min. | Surface Roughness, $R_A$ |
|---|---|---|
| 0.003 | 1.47 | 30 |
| 0.004 | 4.42 | 30 |
| 0.0045 | 7.36 | 19 |
| 0.0055 | 10.31 | 30 |
| 0.007 | 13.25 | 32 |
| 0.007 | 16.20 | 12 |
| 0.007 | 19.14 | 18 |
| 0.007 | 22.09 | 24 |
| 0.0075 | 25.03 | 32 |
| 0.008 | 27.98 | 22 |
| 0.009 | 30.92 | 29 |
| 0.009 | 33.87 | 26 |
| 0.009 | 36.81 | 22 |
| 0.010 | 39.80 | 26 |
| 0.010 | 42.70 | 38 |
| 0.010 | 45.64 | 27 |
| 0.010 | 48.59 | 40 |
| 0.011 | 51.63 | 23 |
| 0.0115 | 54.43 | 32 |
| 0.0115 | 57.42 | 37 |
| 0.013 | 60.37 | 26 |
| 0.013 | 63.31 | 33 |
| 0.0135 | 66.26 | 33 |
| 0.0135 | 69.20 | 39 |
| 0.0135 | 72.15 | 33 |
| 0.014 | 75.09 | 24 |
| 0.014 | 78.04 | 24 |
| 0.014 | 80.98 | 22 |
| 0.014 | 83.93 | 32 |
| 0.014 | 86.87 | 32 |
| 0.014 | 89.82 | 32 |
| 0.0145 | 92.76 | 33 |
| 0.0145 | 95.81 | 45 |
| 0.015 | 98.65 | 28 |
| 0.016 | 101.60 | 38 |

## *Data Table 10* / END MILLING A710 STEEL USING 3 FLUTE END MILLS

### Effect of Cutting Time and Tool Wear on Surface Roughness, $R_A$

Cutter: Putnam Brand ¾ inch Dia., 3 Flute End Mill, M2 High Speed Steel
Feed Rate: 0.004 ipt
Axial Depth of Cut: 0.750 inch (1 Dia.)
Radial Depth of Cut: 0.1875 inch (Dia./4)
Cutting Fluid: Trim Sol, 1:20
Setup of Cutter to Work piece: Down milling

M2 High Speed Steel

| Corner Wear, inch | Cutting Time, min. | Surface Roughness, $R_A$ |
|---|---|---|
| 0.006 | 1.96 | 37 |
| 0.008 | 5.89 | 43 |
| 0.008 | 9.82 | 50 |
| 0.010 | 13.74 | 43 |
| 0.012 | 17.67 | 46 |
| 0.012 | 21.60 | 74 |
| 0.015 | 25.53 | 42 |
| 0.016 | 29.45 | 48 |

## NOTES