Comparative Machinability of Brasses, Steels and Aluminum Alloys:

CDA's Universal Machinability Index

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Abstract

The large number of machinability tests developed in the past are limited by their ability to compare materials of different classes, e.g., ferrous vs. non-ferrous metals, and by the extrapolation of test data to machine shop practice. Publication of ASTM E618, a machinability test that evaluates materials under production-scale conditions using a commercial automatic screw machine, does provide the basis for making such a comparison and can offer practical information to the machinist. However the ASTM test method has heretofore been applied almost exclusively to steels or to metals of similar classes. A technique was therefore developed whereby ASTM E618 can be applied to a number of different materials, including brasses, carbon and leaded steels and aluminum alloys. A graphical method of data analysis has also been developed which enables (1) formulation of a universal machinability rating by direct comparison of different materials and (2) prediction of both theoretical and actual production rates for arbitrary screw-machine products based on workpiece dimensions, workpiece material and the type of cutting tool employed. The test method and data analysis are described. Predicted production rates are compared with those experienced by a commercial screw-machine operator.

INTRODUCTION

Machinability is a consideration in the materials selection process for automatic screw machine parts. The ease with which a metal can be machined is one of the principle factors affecting a product's utility, quality and cost. The usefulness of a means to predict machinability is obvious. Unfortunately, machinability is so complex a subject that it cannot be unambiguously defined. Depending on the application, machinability may be seen in terms of tool wear rate, total power consumption, attainable surface finish or several other benchmarks. Machinability - therefore depends a great deal on the viewpoint of the observer; in fact, the criteria for one application frequently conflict with those for another.[1]

Another difficulty is that the property we call machinability depends on the joint influences of a large number of factors, many of which are quite complex. For example, machinability is certainly closely linked to the physical and mechanical properties of the workpiece: hard, brittle metals being generally more difficult to machine than soft, ductile ones, Figure I. But very ductile metals, such as pure copper, stainless steels and some aluminum alloys tend to form long stringy chips, which makes them at least trouble-some to machine. Machinability is also strongly dependent on the type and geometry of tool used, the cutting operation, the machine tool, metallurgical structure of the tool and workpiece, the cutting/cooling fluid, and the machinist's skill and experience. It is therefore not surprising that some observers have concluded that machinability simply cannot be precisely described and that, despite the considerable body of research that has been devoted to the subject, the term can have little meaning except in a loose quantitative sense.[1]

The ability to quantify machinability remains an important goal, however. The ability to predict machining rates, and therefore production economics, would be especially beneficial to the automatic screw machine parts industry, where high productivity is essential. A quantitative machinability index would also rationalize the materials selection decision which, for screw machine parts, is still based as much on tradition as on machinability data. The work reported here attempts to provide a means to predict machinability in terms of production rate for automatic screw machine products for several combinations of workpiece and tool material.

MACHINABILITY TESTS

A number of tests have been devised to place at least some unit of measure on machinability. The tests, which take many forms, can be classified as being either absolute or ranking. Absolute tests seek to define machinability through analytical expressions using materials properties, i.e., they imply that "machinability" is itself a derivative material property. Ranking tests simply compare the performance of two or more workpiece (or tool) materials under given experimental conditions. Ranking tests are probably more familiar, among other things, they have been used to create the familiar "machinability index" ratings. Many absolute and ranking tests are now avail-able; Mills and Redford[2] have recently tabulated 13 recognized procedures, including an international standard, ISO 3685-1977.

The earliest attempts to quantify machinability date back to the industrial revolution, but it was not until Taylor's classic paper in 1906 that the subject began to be addressed analytically.[3] Significant advances in understanding the machining process were made about 35 years later by Ernst and Merchant,[4] whose thermodynamic approach proposed a specific cutting energy, P_s, which describes the efficiency of the cutting process:

$$\mathbf{P_s = \frac{P_m}{Z_w} = \frac{F_c}{A_c}} \qquad \textbf{[1]}$$

where

$\mathbf{P_m = F_cV}$ = the rate of energy consumption during machining;

$\mathbf{F_c}$ = cutting force in the direction of cutting;

$\mathbf{Z_w}$ = metal removal rate;

$\mathbf{A_c}$ = cross-sectional area of the undeformed chip, and

$\mathbf{V}$ = cutting speed.

$\mathbf{P_s}$ is affected by cutting speed, feed and tool geometry. The theory does not specifically provide for materials comparisons in that $\mathbf{P_s}$ can vary considerably for a particular material. Cutting energy does tend to become constant at high speeds and large feeds, therefore Ernst and Merchant, and Lee and Shaffer[5] later on, imply that the dominant material property is related to the workpiece material's shear strength. (Experimental work does in fact show that a material's shear stress remains constant over a wide range of cutting conditions.) Thermodynamics also suggests that the non-friction heat generated during machining is a function of the workpiece material's physical properties. One proposal is that it should therefore be possible to describe machinability in terms of a "thermal number" **R**, which takes the relevant properties into account:

$$\mathbf{R = pcva/k} \qquad \textbf{[2]}$$

where

p = density

c = heat capacity

v = a velocity related to cutting speed

a = chip area

k = workpiece thermal conductivity

Analytical treatments can provide ranking data, such as the following list of estimated cutting energies published by a commercial tool supplier:[6]

WORKPIECE	ENERGY CONSUMED, HP/in³/min
Magnesium Alloy	0.25
Aluminum Alloy	0.40
Free Cutting Brass	0.50
Leaded Steel	0.70
Copper	0.80
Cast Iron	1.40

Simple ranking systems have also been constructed on the basis of a single mechanical property such as the hardness-based system illustrated in Figure 1. More sophisticated attempts to relate physical and mechanical properties with machining conditions in order to predict machinability have been made by, among others, Boulger, *et al*,[7,8] Czaplicki[9], Henkin and Datsko,[10] and Janitsky.[11] Boulger, for example, proposes that machinability (in terms of the $\mathbf{V_{60}}$ machining speed) is a function of Brinnell hardness, $\mathbf{H_B}$, thermal conductivity, **B**, length of cut, **L**, and the reduction in area in a standard tensile test, $\mathbf{A_r}$:

$$\mathbf{V_{60}\ \alpha\ (B/LH_B)(1 - A_r/100)^{1/2}} \qquad \textbf{[3]}$$

Boulger's test, and others like it, do give consistent and reproducible data when applied to a particular class of materials, such as the leaded steels. These tests do not however permit valid comparisons between different classes of materials, e.g., between steels and non-ferrous metals. They also limit the measure of machinability to one parameter, in this case machining speed.

In summary, basic theory (expression [1]) implies that machinability can be generalized and therefore should be predictable given the proper test parameters. Attempts at defining these parameters ([2], [3]) have been moderately successful, but none have so far been able to provide a universal ranking system. Also missing is a description of machinability that encompasses such factors as surface finish and tool wear.

ASTM METHOD E618-77T

An important step toward providing utilitarian machinability data was taken in 1977 by the publication of ASTM E618-77T, Tentative Method for Evaluating Machining Performance Using an Automatic Screw/Bar Machine.[12] The standard was developed by the ASTM Subcommittee E28.08 on Machinability Test Methods and was specifically designed to provide engineers and machinists with a means to rank materials in terms that have practical significance, using standards to which these individuals are accustomed to working. Method E618 is therefore a ranking-type, production-oriented test but, as will be shown, it is singularly significant in that it can also be used to generate broadly applicable, quantitative data. A brief description follows:

ASTM E618 was designed to simulate mass-production conditions in a controlled environment using any single- or multiple-spindle automatic screw machine. It is based on the production, in quantity, of

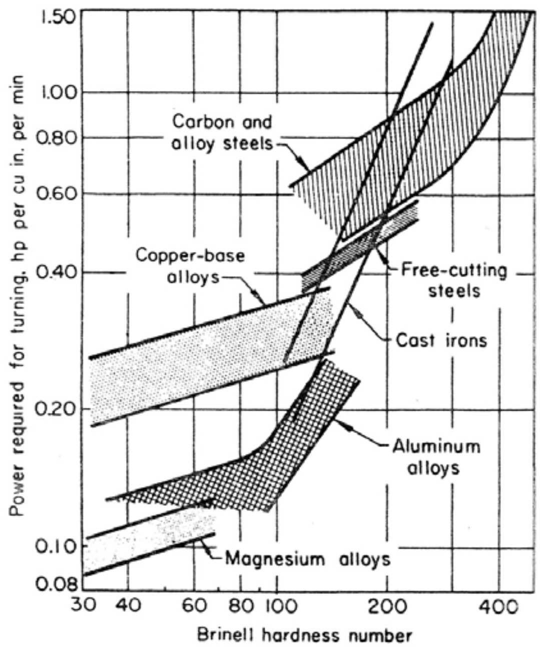

Figure 1. Influence of workpiece hardness on machinability. (Reprinted from ASM Metals Handbook, 8th Edition, Vol. 3, ASM International, Metals Park.)

the standard part illustrated in Figure 2. The part itself was designed to make use of the three most common screw machine operations: rough turning, finish turning and drilling. The part is machined from bar stock and its scrap ratio, 0.70, is fairly typical of commercial screw-machined products. (Scrap ratio is the weight of turnings divided by the weight of raw material needed to make a part. It is used by screw machine operators to estimate their *net* materials costs, i.e., the cost of the raw material less an allowance for the value of the turnings, if any.) The dimensions of the part are fixed by the standard, but may be altered to suit a larger- or smaller-diameter raw material (bar stock) if all dimensional ratios are kept in proportion to the sizes given in Figure **2.**

The machinability "data point" the test yields is equally meaningful: it is simply the maximum number of standard parts that can be produced based on one form tool change in eight hours. (An eight-hour tool life has practical significance for any machinist, for obvious reasons.) The criteria on which the necessity for a tool change (or sharpening) is predicated are equally practical: they are reached when either dimensional tolerances or surface finish exceed stipulated limits. In ASTM E618, these include a 0.005 in (0.13 mm) increase in diameter and 300 µin (0.023 mm) arithmetic average (AA) surface finish for rough-formed surfaces and a 0.003 in (0.08 mm) increase in diameter and 150 µin (0.012 mm) surface finish for finish-formed surfaces). Other criteria may be used but they must be clearly stated and applied equally to all candidate materials. Tools must be of either M2 (for form tools) or M7 (for drills) high-speed steel. If other steels are used they must be identified and must be used for all candidate materials. All tools must be ground to geometries fixed by the standard. The machining sequence is specified and based on normal industrial practice. The screw machine on which the tests are performed must be "calibrated" to determine its particular production limits. Commercial coolants are to be used.

To conduct the test, samples are taken at intervals during a machining campaign in which speed and feed are fixed. Samples are inspected for dimension and surface finish and the point (number of parts produced for that particular speed/feed setting) at which the prescribed limits are exceeded is recorded. Speed and feed are then adjusted to increase or decrease production rate, depending on whether the previous tool life was less or more than eight hours. Another campaign is then begun. When sufficient data have been taken the number of parts produced are plotted on semi-logarithmic paper as a function of tool life until the "production rate" in parts per hour for an eight-hour tool life can be interpolated. This number is reported as the machinability rating of the material under test.

The ASTM test is neither simple nor inexpensive. Considerable time is required to establish the machine parameters, conduct the machining and analyze the results. Depending on the material, from several hundred to several thousand pounds of bar stock are typically required. Despite these drawbacks, ASTM E618 has the over-riding advantage that it is the only test as yet devised which can yield commercially relevant ratings for both materials selections and machine shop cost estimates.

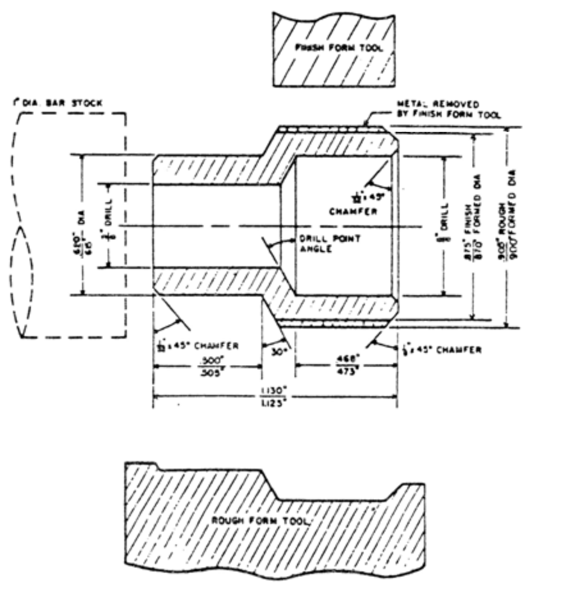

Figure 2. Automatic screw machine part required for ASTM E618. The standard part is designed to be made from one-inch (25-mm) diameter bar check. The part used in this work was down-sized to permit use of 0.75-in (19-mm) rod; this is permitted under ASTM E618 if done for all materials. (Reprinted from Ref. 12)

THE CDA TEST PROGRAM

ASTM E618 was designed primarily to evaluate the machinability of steels. Prior to the publication of the test method, it had been normal commercial practice for steel suppliers to designate the machinability of their products based on one – often arbitrary – “machinability index” or another. The ASTM method therefore provides a uniform way to differentiate between steels by establishing a standard comparison method.

Free-machining steels containing lead, tellurium and other machinability-enhancing agents are commonly compared with competing non-ferrous alloys, notably the free-cutting, leaded brasses such as Alloy 360. It is implied, somewhat misleadingly, that steels and brass alloys can be equated. For example, the most machinable steels and the most machinable brass (Alloy 360, Free-Cutting Brass) are each designated, by their respective suppliers, as having a machinability index of 100 even though both ratings are based on evaluations conducted against other materials of the same type, i.e., steels against steels, brasses against other copper-base alloys.

The Copper Development Association Inc. (CDA) recognized several years ago that the new ASTM method might provide a way to evaluate *all* materials on an equal basis and determine quantitatively what the actual machinability ratings of the copper-base alloys should be. At the same time, CDA saw that the ASTM method could be utilized to compare, unambiguously, how the copper metals performed against competing free-machining steels. CDA therefore initiated a test program to evaluate the machinability of copper alloys according to the requirements of ASTM E618-77T. The program was shortly thereafter broadened to include other materials.

The copper alloys evaluated in the test program included Alloys 360 (Free-Cutting Brass), 340 (Medium Leaded Brass) and 454 (Naval Brass, Uninhibited). Ferrous materials tested included the mild steel AISI 1213 and its leaded variant, AISI 12L13, Aluminum alloy 2011-T3 was also included in the experimental program. All of these alloys are common feedstocks for automatic screw machine products. It should be noted that the brasses (in their selected tempers) encompass approximately the same strength range as the mild, leaded steels and as such could be equally viable in a materials selection process for screw-machine products. Nominal compositions and mechanical properties of the test workpiece materials are given in Table I.

TEST PROCEDURE - All tests were conducted at a commercial screw-machine shop using a 6-spindle Model 60 New Britain machine. In order to conserve material, the standard ASTM specimen was down-sized (for all materials) to permit the use of 3/4-in bar stock.

Tests were begun by standardizing the machine using the mild steel (and leaded steel) feedstock and the recommended M2 tool steel. Some tests were also conducted using A2 (an air-hardening grade) and O1 (oil-hardening) tool steels, but the latter grade was only utilized to a limited extent because of its relatively short life.

A typical set of data are shown in Figure **3.** Dimensional conformance and surface finish are plotted as functions of the number of parts produced. The point at which either limit (diameter or surface roughness) is exceeded is denoted as the tool life for the machining conditions indicated. A least squares fit was used where needed to accommodate the scatter typically found in machinability tests of this type. Tool life data were then re-plotted to determine the maximum theoretical production rate for an eight-hour tool life, Figure **4.** A summary of all data taken in the study is presented in Table **II**.

A considerable amount of material, more than 10,000 pounds of brass and steel, was consumed to conduct the tests. Since about 80,000 of the test parts were eventually produced it is fair to say that the test approximated normal commercial machine-shop practice.

Early in the testing program it became evident that using the designated M2 tool steel would result in an inordinately high consumption of feedstock, particularly - brass, which produced almost insignificant wear on the tooling. To reduce testing time, it was decided to utilize the intermediate A2 grade (as well as O1) for some of the tests. This required that a relationship between the performance of the M2, A2 and O1 steels had to be established. Tests were run at several combinations of speed and feed for each tool steel and the ratio of theoretical machinabilities compared for the several workpiece materials. The results, shown below, indicate that the ratio of performance for the O1 and A2 tool to that of M2 steels are similar enough to permit substitution while testing the selection of workpiece materials investigated here. One benefit of this finding is that it broadens the applicability of the method to include a wider range of machining performance scenarios.

Table I Nominal Compositions and Mechanical Properties of Test Materials, ksi (MPa)

Alloy	Cu	Pb	Fe	Zn	Al	C	Others	YS	TS	%El	Hdns	Sh.Str.
C36000: Free Cutting Brass, ½ H	61.5	3.1	--	35.4	--	--		52 (358)	68 (469)	18	R_b80	38 (262)
C34000: Med. Leaded Brass, ¼ H	63.5	1.0	--	35.5	--	--		42 (290)	55 (379)	40	R_b60	36 (248)
C46400: Naval Brass, Uninhibited, ½ H	60	1	--	39.2	--	--	0.8Sn	57 (393)	80 (551)	20	R_b85	40 (276)
2011-T3: Wrought Al Alloy	5.5	0.4	--	--	Bal.	00	0.4Bi	43 (296)	55 (379)	15	BHN95	--
1213: Re-P, Re-S C-Steel, Cold Drawn	--	--	Bal	--	--	0.13 max.	0.70-1.0Mn	60 (414)	78 (538)	10	BHN167	--
12L14: Leaded Free-Machining Steel	--	0.15-0.35	Bal	--	--	0.13 max	0.70-1.00	60 (414)	89 (613)	10	BHN167	

Table II Production Rate Data for Brass and Steel Automatic Screw Machine Products

Part	Machine	Scrap Ratio	ΔV, In^3 (mm^3)	$TPR_{Stl'}$ Pcs/h	$TPR_{Br'}$ Pcs/h	$MTPR_{Stl'}$ Pcs/h	$MTPR_{Br'}$ Pcs/h'	$MPR_{Br}/MTPR_{Br}$	$MPR_{Stl}/MTPR_{Stl}$
Flare Nut	Davenport Model B	0.58	0.132 (2165)	900	1125	2760	13,400	0.084	0.326
Spacer	Davenport Model B	0.79	0.199 (3265	600	1028	1550	7500	0.137	0.388
Poppet	Davenport Model B	0.62	0.26 (4266)	600	900	1150	5600	0.161	0.508
Can	Acme Model 51	0.64	0.207 (3396)	524	1019	1450	7100	0.143	0.362
Setscrew	1-in. Acme	0.42	0.118 (1936)	1501	2299	3400	16,500	0.139	0.441
Pulley	1 ¼-in. Acme RA-6	0.38	0.315 (5168)	570	914	1000	4750	0.192	0.571
Body	1-in. Acme	0.77	0.103 (1690)	3179	4260	4550	22,000	0.194	0.700
Hub	New Britain Model 60	0.586	0.204 (3347	788	1596	1500	7300	0.219	0.526
E618	Mew Britain Model 60	0.70	0.266 (4364)	1133	5300	1133	5300	1.0	1.0

MATERIAL	P.R.M2/P.R.O1	P.R.M2/P.R.A2	P.R.A2/P.R.O1
C1213	2.817	1.976	1.425
C12L14	2.811	1.974	1.424
C46400	2.720	2.021	1.338
C36000	2.704	2.021	1.338
Average	2.763	1.9705	1.403

P.R. = Production rate for 8-hr tool life

Throughout the test, all production rates were calculated on the basis of their theoretical values. That is, machining times (and production rates) were based on the assumption that the tools were always cutting. This is obviously not the case, but using the theoretical value cancels out all dead time during which the machine feeds, or when tools dwell or index. Since such dead time normally differs from machine to machine the theoretical values can be used to compare materials universally, if allowance is made for individual machine operating characteristics. All data reported herein is in the form of theoretical production rates.

The resulting "universal machinability index" data, i.e., maximum production rates giving an eight-hour tool life for the several workpiece materials, is shown in the bar graph in Figure **5.** As might be expected based on experience, the Free-Cutting Brass, Alloy C36000, demonstrated the highest machinability rating of all the test materials, followed by Alloy C34000, 2011-T3 aluminum, Alloy C46400 and the carbon steels. Because sub-sized (0.75 in, 19 mm) specimens were used in CDA's testing program, data shown in the figure were normalized to C36000 = 100. Theoretical production rates as developed from the ASTM method were: Alloy C36000 - 5300 pcs/h; Alloy – 3789; Alloy C46400 – 2679; Alloy 2013-T3 – 2622; 12L14 Steel – 1133; 1213 Steel – 952, all using M2 tooling. Use of A2 and O1 tolling resulted in lower ratings for all materials although the materials' relative ranking remained the same. It was consistently found, however, that the "machinability" (maximum theoretical production rate) of the Free-Cutting Brass was some five times that of leaded steel.

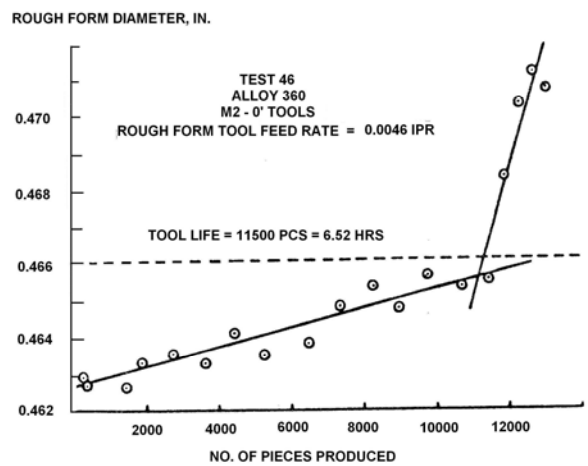

Figure 3. Typical data from a machining campaign under ASTM E618. Rough- and finish-formed diameters and surface finish are plotted against the number of specimens machined at a given production rate (speed and feed settings) until fixed limits on dimensions and roughness are exceeded. Least squares fitting is applied where necessary to account for scatter.

NOMOGRAPH FOR ESTIMATING PRODUCTION RATES

The internally consistent nature of the data suggested that it might be possible to predict machinability (i.e., production rates in terms of ASTM E618) in a more general sense. If successful, this would provide the basis for a quantitative prediction of production rate for any combination of screw-machine, tool and workpiece material for which ASTM E618 data existed.

However a review of machinability theory led rapidly to the realization that no unique function capable of treating production rate data exists and that deriving such a function, given the many complex factors involved, would not be possible. A graphical solution, i.e., a nomograph,

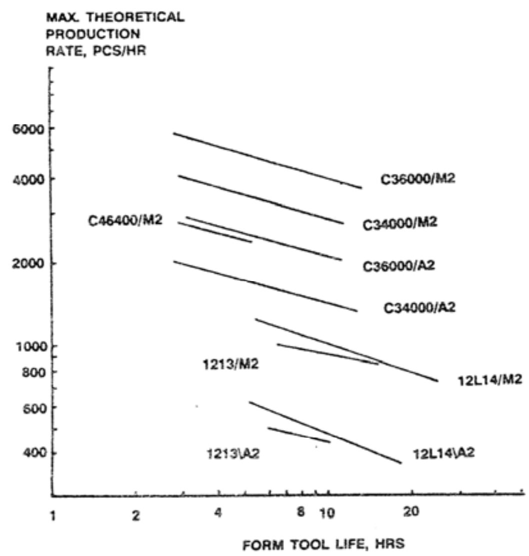

Figure 4. Machining data from several campaigns re-plotted to determine the production rate requiring one tool change in eight hours. This value of production rate is taken as the machinability rating of the material under test.

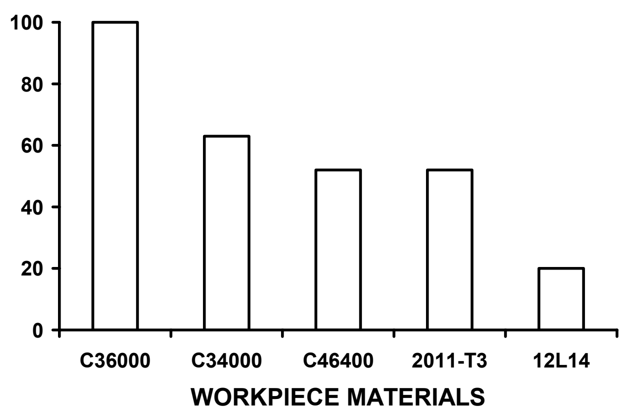

Figure 5. Universal machinability ratings (maximum theoretical production rates for eight-hour M2 tool life) of common automatic screw machine materials determined using ASTM E618. Data are normalized to Alloy C36000 (Free-Cutting Brass) = 100 because 0.75 in (19 mm) dia. specimens were used.

was therefore attempted. Nomographs hold the advantage that machine shop operators, especially those who do not as yet utilize computer aids in production planning, are familiar with their use.

Taylor's general expression for machinability is expressed in the form:

$$\mathbf{V^pS^qa^rT = C_2} \qquad [4]$$

where

V = cutting speed
S = feed rate
a = width of the chip
T = tool life

and $\mathbf{C_2}$, **p**, **q** and **r** are constants for a particular class of materials. If, as Mills and Redford[2] have noted, the time to machine a part,

$$\mathbf{T_m = \pi DL/SV} \text{ for simple turning} \qquad [5]$$

where

D = Diameter
L = Length of cut

and that the number of parts/tool change,

$$\mathbf{P = T/T_m} \qquad [6]$$

Since the factors $\mathbf{a^r}$ and $\mathbf{\pi DL}$ represent a term for the quantity of material removed, **v',** for a particular machining operation, then by combining and rearranging terms it is possible to construct an expression of the general form:

$$\mathbf{P = Cf_1(S,V)/f_2(v')} \qquad [7]$$

or $$\log\mathbf{P} = \log\mathbf{C} + \log f_1(\mathbf{S,V}) - \log f_2(\mathbf{v'}). \qquad [7a]$$

This expression can be represented graphically using the customary rules of nomograph construction. It is not necessary to know the exact form of the expressions for feed and speed if the data are internally consistent. Also, workpiece and tool properties will be embodied in the constant, **C**, for which a separate set of graphical representations can be constructed.

When the theoretical production rate data from which Figure **5** was constructed, including corresponding data taken using A2 and O1 tooling, are plotted with respect to the type of tooling, the nomograph in Figure **6** results. It was constructed empirically as follows:

For one of the test materials, a line was first drawn from the “Volume of Metal Removed” axis at right through an axis representing the maximum theoretical production rate to an arbitrary reference line. The intersection on the “Volume of Metal Removed” axis represents the volume of turnings (0.266 in^3, 4364 mm^3) for the ASTM test piece. A logarithmic scale was chosen for the production rate axis to accommodate the span of the data. A line was then drawn from the reference line through an, again arbitrarily chosen, point on a line representing the tooling material (M2) to locate a point on the “Workpiece Material” axis. This process was then repeated for the same test material machined with another grade of tooling (A2). In this case

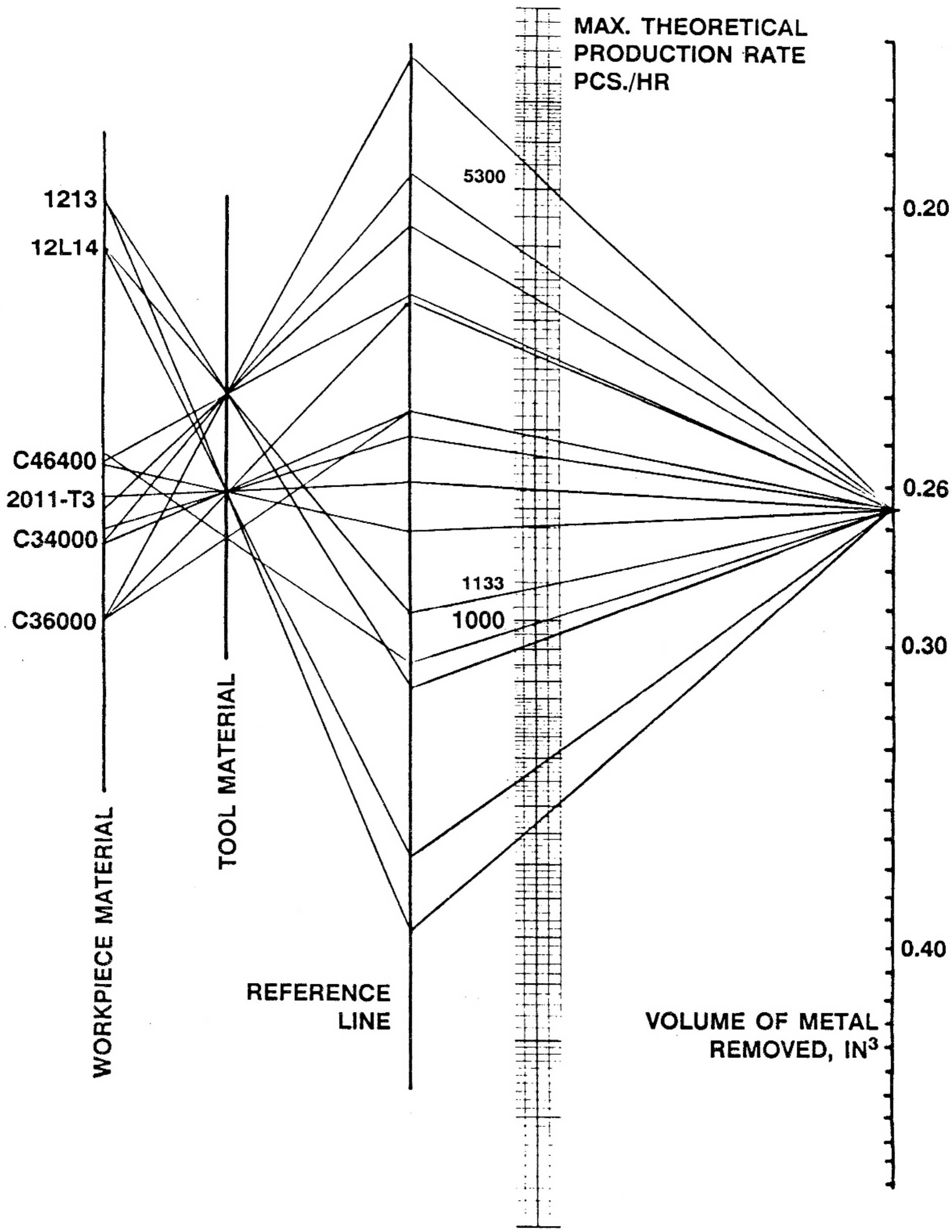

Figure 6. Nomograph constructed from machinability data taken using ASTM E618 using several combinations of workpiece and tool material. Theoretical production rates (a universal machinability index) exclude any dwell, index and feed times. Data was taken using a New Britain Model 60 six-spindle machine, but presentation of theoretical production rates can be used to compare production on any automatic screw machine.

the intersection on the “Reference” axis was connected with the point on the “Workpiece Material” axis determined earlier, thus establishing the point for the second grade of tooling, i.e., graphically illustrating the relationship between the two grades of tool steel. The procedure was repeated once more using data taken with the third tool steel (01). The relationship among the three tooling materials was thereby fixed for the first material under test, Alloy C36000 in this case.

Data from a different workpiece was then plotted similarly, but using the “Tooling Material” intersections previously established, to locate the second workpiece’s relative standing on the “Workpiece Material” axis. At this stage little other than the relative position of the tool steels could be inferred from the figure. When the second material was plotted using the first material’s “Tool Material” intersections, however, it was found that the final intersection on the “Workpiece Material” axis fell very nearly at a single point, implying that the relationship among the three tool steels, previously established, was valid for the second material as well. The same was found for the remainder of the test materials. The interesting point of this observation is that the relationship among the three tool steels appears to remain constant, irrespective of the workpiece involved, at least for the five workpiece materials tested. The nomograph in Figure **6** therefore illustrates graphically the relationship among the workpiece materials *under the defined conditions of maximum theoretical productivity as set forth in ASTM E618.*

COMPARISON WITH COMMERCIAL PRACTICE

The above solution appears to accommodate machining data for the ASTM 5618 test fairly well although it is understood that the ASTM test piece as well as the machining conditions were closely controlled in this instance. The “Universal Machinability Index” values derived in the test program were compared with production rate data from two commercial screw machine houses. The machine shops routinely produce parts in both brass and steel and it was therefore assumed that both metals were machined at optimum (although certainly not maximum) production rates.

The eight products examined were produced in, or estimated for, both leaded steel (12L14) and Free-Cutting Brass (C36000) They were produced on five models of three common multi-spindle automatic screw machines using M2 tooling. A few operations were performed with carbide tooling, but these were not rate-determining. The products encompassed a reasonably broad range of scrap ratios (weight of metal removed/weight of raw material) and of the absolute volume of metal removed per part.

Production rate data (known or estimated for highest practical rate, generally based on handbook recommendations, prior shop practice or limitations dictated by the particular part’s configuration) were converted to theoretical production rates by subtracting dwell and index/feed times taken from the several machines’ technical data. These are listed in Table II and are shown plotted on the nomograph axes, Figure **7**. The “Volume of Metal Removed” axis is plotted inversely, top to bottom, to portray the inverse proportionality expected between production rate and amount of metal machined. The intersections along this line refer to the several specimens examined. It was not expected that commercial products would yield as concise results as the E618-based test program, and this in fact was the case.

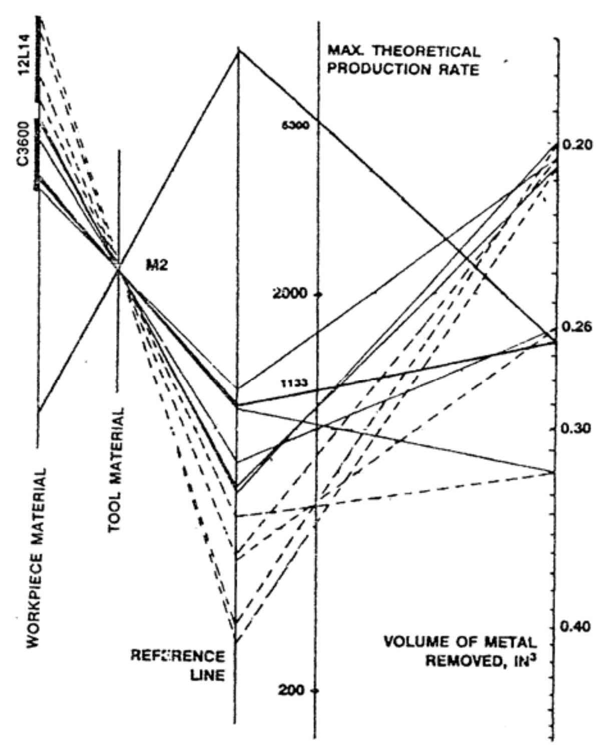

Figure 7. Comparison of machinability for several brass and steal commercial screw machine products based on theoretical production rates derived from actual production rate data. Data are plotted on axes similar to those for the nomograph shown in Figure 6. Location of brass and steel on the “Workpiece Material” axis, left, based on ASTM E618 are shown for comparison. The shift in these points, as well as scatter in the data, result from several operator-and machine-related factors. Heavy lines are from Figure 6, included for reference.

Figure 7 shows that the degree of scatter for commercial parts is considerably greater than for the ASTM part, although the difference in theoretical production rates for brass and steel, i.e., their relative "machinabilities" is quite evident. No single factor can be identified to account for this scatter although in several cases production rates would have been considerably closer to those predicted by the ASTM method if spindle speeds were raised above those based on handbook values. That higher speeds were not chosen was often simply the result of conservatism on the part of the machine tool operators apparently concerned over the possibility of excessive machine wear on spindle bearings and slides.

As a result of these several factors, theoretical production rates in commercial practice were considerably lower than they might have been. Differences, expressed as ratios, between actual theoretical rates (i.e., corrected for dwell and index/feed times, to permit comparison) in the two machine shops and maximum theoretical rates (predicted by the nomograph, Figure **6**, i.e., based on an eight-hour tool life) are listed in Table **II**. It was observed that the ratio of actual theoretical to maximum theoretical rates in parts made from leaded steel ranged from 0.326 to 0.700 with a mean of 0.452. That is, the parts were produced on average at less than one-half the maximum theoretical rate, or somewhat more than one-half the maximum actual rate, counting non-cutting time. When measured in terms of theoretical rates there appeared to be little difference between the performance of the several machines used. The influence of dwell and index/feed times, which varied considerably from part to part and machine to machine, respectively, could not be generalized due to the limited number of samples investigated.

The ratio of actual to ideal maximum theoretical rates for Alloy C36000 (Free-Cutting Brass) parts ranged from 0.084 to 0.219 with a mean of 0.147. That is, the screw machines were only taking advantage of somewhat more than 15% (counting non-cutting time) of the theoretical machinability of the brass alloy. Again, there appeared to be little consistent difference among machines with regard to the efficiency with which they were able to produce brass parts. However the average ratio of actual to theoretical times for brass relative to that for steel for Davenport Model B machines was 0.97; that for Acme-Gridley machines (three models) was 0.88 and that for New Britain Model 60 machines was 0.83. Measured on the basis of production practice for this small number of samples, Davenport automatic screw machines therefore tend to be operated to cut brass somewhat more efficiently than steel, which may account for their use in screw machine houses with a significant proportion of brass in their production program.

CONCLUSIONS

Although the CDA machinability test program was limited in scope, it is possible to draw some initial conclusions regarding both the ASTM test method and the data generated by its use:

1. ASTM E618, while developed primarily to evaluate the machinability of steels, appears to be equally applicable to non-ferrous alloys. In particular, it has been demonstrated that machinability data for carbon and leaded steels, one aluminum alloy and three copper-base alloys are consistent.
2. It has also been demonstrated that it is possible to establish consistent relationships among three common types of cutting materials, and that this enables the intrinsically time-consuming ASTM method to be shortened somewhat. It is also possible to reduce the size of the standard ASTM test part (as permitted under the method) and thus reduce both machining time and raw material requirements. Further, the assumed relationship between production rate and the amount of metal removed could not be verified since ASTM E618 parts of only one size were produced. Since the test apparently yields consistent results for specimens of one size it would be instructive to manufacture parts of several sizes under identical cutting conditions to test the validity of the assumed volume/production rate relationship.
3. Using ASTM E618 it is possible to develop a universal machinability index that is valid for both ferrous and non-ferrous materials. This permits the comparison of materials with widely different mechanical properties. Because the ASTM method is conducted on commercial automatic screw machines and because its results are reported in terms of production rates, the universal machinability index can provide technologically useful information to screw machine operators. It is currently only possible to present this information in a ranking fashion but accumulation of sufficient data may eventually permit the prediction of actual production rates based solely on product geometry (amount of metal removed) and workpiece and cutting tool materials. Such information would be invaluable when selecting materials for automatic screw machine products.
4. When generated using ASTM E618, the universal machinability rating of Free-Cutting Brass, taken as 100, implies a universal machinability rating of 66 for Medium Leaded Brass, Alloy C34000; about 50 for both Naval Brass, Uninhibited, Alloy C46400 and Aluminum Alloy 2011-T3, and 21 for Leaded Free-Machining Steel 12L14.
5. Based on the limited number of screw machine parts examined, commercial practice exploits on average about one-half the maximum theoretical production rate of leaded steel and only about 15% of the maximum theoretical production rate of Free-Cutting Brass. Even when account is taken of unavoidable non-cutting time, i.e., as in actual production rates, it appears that current automatic screw machines do not take full advantage of the theoretical production rates of leaded steel and - especially - Free-Cutting Brass. Obviously, development of faster automatic screw machines would provide significant benefits to the screw machine products industry.

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