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HIGH SPEED MACHINING OF BRASS ROD ALLOYS

G. Adinamis[1], F. Gorsler[1], A. Estelle[2]*
[1]TechSolve, Inc., Cincinnati, Ohio, USA
[2]Copper Development Association Inc., McLean, Virginia, USA
*Corresponding author; e-mail: adam.estelle@copperalliance.us

Abstract
Brass is known for excellent machinability, but its ultimate productivity potential with high speed machining requires further study. An extensive testing program was conducted in laboratory and production settings on representative brass rod alloys using modern machine tools. Machinability data collected for turning, drilling and milling offers new insights on the effects of increasing speed, feed rate and depth of cut on tool life, efficiency, surface integrity and chip formation. The results show that advancements in machine tool technology, coupled with the underutilized high speed machining capabilities of brass, offer new opportunities for manufacturers to become more productive and profitable.

Keywords:
Brass; Machinability; High speed machining; Turning; Drilling; Milling; Cutting speed; Tool life; Surface roughness; Chip formation; CNC; Throughput; Productivity; Profitability; Steel; Stainless steel

1 INTRODUCTION

Brass alloys offer a unique combination of material attributes including excellent machinability, high electrical and thermal conductivity, good strength, ductility and corrosion resistance, non-magnetism, and high scrap value. Brasses are therefore widely used in numerous industries including plumbing, automotive, machinery, electrical and electronic, aerospace and medical.

Adding small amounts of lead to brass improves machinability by enabling free-flowing chips and lubrication of cutting tools. For applications such as potable water components where regulations restrict lead, a variety of non-leaded brasses are available. In general, non-leaded brasses are more difficult to cut than leaded alloys and thus require different machining strategies [Nobel 2014].

Considering the range in machinability and material properties of different commercially available brass alloys, machining handbooks are valuable resources with practical guidance on recommended tooling and cutting parameters and state of the art practices [DKI 2010]. However, handbook values can be overly conservative and may not reflect more aggressive cutting parameters that can be achieved on advanced machine tools with high speed spindles. For instance, a large scale machinability evaluation of brasses suggested that commercial practice only exploits about 15% of the maximum theoretical production rate of free-cutting brass [Thiele 1990].

Irrespective of the material, high speed machining offers wide ranging benefits to manufacturers equipped with modern machine tools and processes. Greater throughput achieved with higher metal removal rates can boost profitability, increase machine utilization and expand production capacity. However, these gains are indeed dependent on the inherent machinability of the base material and the attainable cutting speeds that can be maintained for practical production periods [Schultz 1992]. While high speed machining of aluminum and aerospace alloys has been widely studied [Wang 2014], similar information on brasses is limited.

To assess the high speed machining potential and productivity upside of brass, an extensive testing program was conducted on several free-cutting and non-leaded brass rod alloys using modern CNC machine tools. Leaded low carbon steel and austenitic stainless steel alloys were also evaluated for machinability comparison as steels are occasionally substituted for brass in some applications unless specific technical requirements dictate otherwise.

2 METHODS

A series of single point turning, drilling and peripheral milling tests were performed using carbide tools to measure the effects of increasing cutting speed, feed rate and depth of cut on key productivity and part quality indicators including tool life, surface roughness, chip formation and power factor. Relevant data for each operation were collected across material specific matrices of machining parameters and plotted for further analyses. Data were originally collected in Imperial units which were converted to SI units for this manuscript. All laboratory tests described herein were designed and conducted by TechSolve, Inc. at the M. Eugene Merchant Technology Development Center in Cincinnati, Ohio, USA.

2.1 Materials

Typical chemical compositions and mechanical properties of the tested materials are shown below in Tab. 1 and Tab. 2. The selected alloys represent common feedstocks for automatic screw machine products. For turning tests, round bars in 38.1 or 31.8 mm diameters were utilized for brasses and 101.6 mm diameters were sourced for both steels. For drilling tests, 63.5 and 88.9 mm square bars were utilized for brasses and steels respectively. The 63.5 mm brass square bars were also used for the milling tests.

2.2 Machine tools

A Makino V55 three-axis vertical CNC machining center with a 20,000 RPM spindle was selected for turning, drilling and milling to generate the targeted cutting speeds. Because of the lower speeds and larger diameter workpieces, turning of 304L and 12L14 steels was performed on a horizontal Hardinge Cobra 65 CNC lathe.

2.3 Instrumentation

Tool wear was measured with a Keyence VHX digital 3D microscope. Surface roughness values (Ra, μm) were collected with a Mitutoyo Surftest SJ-410 portable surface roughness tester. Cutting forces were measured with a Kistler type 9121 three-component piezoelectric dynamometer for turning, a two-component Kistler type CH-8408 dynamometer for drilling, and a three-axis Kistler type 9255B dynamometer for milling. Electrical signal outputs from the piezoelectric quartz sensors were fed to a Kistler type 5010 dual mode amplifier for collection and converted to a digital format for analysis.

2.4 Experimental setup

Turning

For brasses, each workpiece was held in the vertical spindle by a chuck collet with the cutting tool, dynamometer and coolant supply mounted on the worktable to form an inverted vertical lathe. A TG150 x 4.88L extension pre-balanced collet chuck was selected to achieve high speeds while maintaining balance and rigidity. The chuck collet was rated up to 20,000 RPM allowing a theoretical speed range between 900 and 2,375 m/min. A horizontal lathe configuration was used for turning tests on the steel alloys.

Drilling

To measure cutting forces, round test pieces were held in a vise centered on a drilling dynamometer with a custom adaptor to measure thrust and torque. Square bars were used for the tool wear tests and were held in toe clamps bolted directly to the worktable. Drills were mounted in a chuck collet and cooled with both external coolant flood and low pressure through the spindle coolant supply.

Milling

Test pieces were held in a vise centered on a milling dynamometer to measure the forces applied to the workpiece by the endmill. Square bar stock for tool wear testing was prepared for work holding by installing dovetail grooves at the bottom which were held by two vises with dovetail fitted soft jaws. The coolant supply used for milling operations involved both flood type and low pressure through the spindle coolant supply.

Tab. 1: Typical chemical compositions of tested brass and steel alloys according to nominal standards.

Alloy	Cu	Pb	Sn	Zn	Fe	P	Ni	Mn	S	Si	Te	C	Cr
C36000	61.5	2.75	-	Rem	0.35 (max)	-	-	-	-	-	-	-	-
C38500	57.0	3.0	-	Rem	0.35 (max)	-	-	-	-	-	-	-	-
C27450	62.5	0.25 (max)	-	Rem	0.35 (max)	-	-	-	-	-	-	-	-
C69240	71.8	0.25 (max)	0.30 (max)	Rem	0.20 (max)	0.09	0.30	0.90	-	2.0	-	-	-
Model 3	86.5	0.09 (max)	0.30 (max)	Rem	0.30 (max)	-	0.30 (max)	-	-	-	0.60	-	-
12L14	-	0.25	-	-	Rem	0.07	-	1.0	0.31	-	-	0.15 (max)	-
S30403 (304L)	-	-	-	-	Rem	0.045 (max)	10.0	2.0 (max)	0.03 (max)	1.0 (max)	-	0.03 (max)	19.0

Tab. 2: Typical mechanical properties for tested brass and steel alloys.

Alloy	Tensile strength (MPa)	Yield strength (MPa)	Elongation (min %)	Hardness (HB)
C36000	345	140	15	107
C38500	330	110	15	107
C27450	295	195	15	107
C69240	480	205	15	183
Model 3	305	200	18	103
12L14	540	415	10	160
S30403 (304L)	485	170	30	191

2.5 Cutting tools

Ideal cutting tools were selected for each material and operation with input from a commercial cutting tool manufacturer. Key criteria for cutting tool selection included suitability for each material class and ability to withstand a broad range of cutting speeds, feed rates and depths of cut. All turning insert geometries were in accordance with ISO 1832, and all tool holders for turning were in accordance with ISO 13399. Further details on tooling by material and operation are presented in Tab. 3.

Turning

For all materials, a CCMT432 tungsten carbide grade insert with a 0.79 mm nose radius was selected. The inserts were held in an SCLCR-2525M-12 tool holder with a -5° lead angle (PSIR). Although the chip breaker geometry is suited for small to medium finishing, it was proven to withstand heavier chip loads up to 0.38 mm/rev with discrete chip formations across a broad range of speeds, feed rates and depths of cut.

Drilling

12.7 mm diameter carbide drills were selected as this is a common size that is readily available and can generate a much higher cutting speed at the perimeter of the cutting edges, allowing for reduced spindle RPM and lower end torque. All drills utilized low pressure through the spindle coolant supply.

Milling

Only the brass alloys were evaluated for milling. An indexable insert was used with a Ø19.05 indexable (2-flute) EC10 tool holder. To isolate cutting forces, only a single insert was used in operation for the material comparison and tool wear tests.

2.6 Coolant

All tests were conducted with TRIM SOL® general purpose water soluble emulsion coolant at 8% concentration.

2.7 Identifying practical speed limits

Turning

The establishment of cutting speed limits for turning was based on two factors. The first being the maximum idle spindle RPM that could be safely achieved with a chuck collet and test specimen. The second was the speed at which at least four hours of tool life could be achieved with acceptable surface roughness and no more than 0.25 mm of flank wear on the insert. General observations were made for potential speed limit indicators such as: chatter, dimensional changes, rapid tool wear or failure, rapid force increases, chip welding to parent metal, and overheating or galling of the workpiece. Tools were examined under magnification for signs of excessive wear that lead to insufficient tool life and productivity.

As the steel alloys were expected to generate higher tool wear, speed limits for turning 12L14 and 304L steels were defined as the maximum speed under which a reasonable tool life of at least 30 minutes could be achieved with acceptable surface roughness and chip formation.

Drilling

Drilling speed limits were based on two factors. The first was the maximum idle spindle RPM that could safely be achieved with a chuck collet and drill. The second was the maximum speed at which at least 1,000 blind holes at 38.1 mm depth (3x drill diameter) could be completed before reaching the end of drill life defined as 0.30 to 0.38 mm of flank wear on either flute, or until the cutting edges of the drill began to show signs of chipping or rounded corners. Exploratory speed tests were conducted using the carbide drills selected for each material and general observations were made for the same potential speed limit indicators described for the turning tests.

Milling

The establishment of cutting speed limits for peripheral milling was based on the maximum speed at which the spindle could rotate without causing chatter on the workpiece, immediate chipping of the insert, or excessive flank wear, at similar speeds achieved for high speed turning with carbide. The end of test for milling was set at 120 min. of continuous cutting or 0.25 mm of flank wear.

2.8 Power factor

In some cases, determining tool life limits proved impractical because of the enormous amount of material required to reach tool failure. Therefore, a measure of machining efficiency known as "power factor" was evaluated which is the amount of power required to remove one cubic centimeter of material in one minute.

Cutting forces used to calculate power factor were collected across a range of speeds, feed rates and depths of cut uniquely suited for each material as determined by the tool life speed limitation tests.

Tab. 3: Cutting tools (ISO 1832) and tool holders (ISO 13399) applied.

Material	Operation	Tool	WC Grade	Coating	Chip breaker / tip angle	Tool holder
Brasses / 304L	Turning	CCMT432	KC5010	TiAlN	Chip Breaker MT-LF Finish (+5° rake)	SCLR-2525M-12
12L14	Turning	CCMT432	K25P	TiN	Chip Breaker MT-LF Finish (+5° rake)	SCLR-2525M-12
Brasses	Drilling	Ø12,70 mm Spiral Flute	KN15	Uncoated	Tip 130°	CAT40 with ER16 HPS Collet
304L / 12L14	Drilling	Ø12,70 mm Spiral Flute	KCM15	TiCN	Tip 135°	CAT40 Shrink Fit HPS Holder
Brasses	Milling	EC1004LD	KC410M	TiB_2	Indexable Milling Insert	EC10 Ø19.05 (2-Flute)

Power factor values from the single point turning tests were derived and calculated as follows:

$$K = \frac{P}{Q} = \frac{Ft \times S \times \left(\frac{1min}{60sec}\right)}{S \times \left(\frac{1000mm}{1m}\right) \times F \times Dc \times \left(\frac{1cm^3}{1000mm^3}\right)}$$

reduced to: $$K = \frac{Ft}{60 \times F \times Dc}$$

K = Power factor ($W/cm^3/min$)
P = Power (W; in N·m/s)
Q = Metal removal rate (cm^3/min)
Ft = Tangential force (N)
S = Cutting speed (m/min)
F = Feed rate (mm/rev)
Dc = Depth of cut (mm)

Turning power factors were calculated across all possible combinations of the cutting parameters shown in Tab. 4.

Tab. 4: Power factor test matrix for turning.

Speed (m/min)			Feed rate (mm/rev)	Depth of cut (mm)
Brasses (all)	**12L14 steel**	**304L steel**		
152	61	30	0.08	0.51
305	122	91	0.13	1.14
610	183	152	0.18	1.78
914	274	244	0.25	2.29
1219	366	305	0.38	3.18

Drilling power factors were derived and calculated across all parameter combinations shown in Tab. 5 as follows:

$$K = \frac{P}{Q} = \frac{T \times N \times \left(\frac{1W}{9.55 \; x \; 10^{-3} \; kW}\right)}{N \times F \times \pi(.5D)^2 \times \left(\frac{1cm^3}{1000mm^3}\right)}$$

reduced to: $$K = \frac{133{,}340 \times T}{F \times D^2}$$

K = Power factor ($W/cm^3/min$)
P = Power (W; in N·m/s)
Q = Metal removal rate (cm^3/min)
T = Torque (N·m)
N = RPM (rev/min)
F = Feed rate (mm/rev)
D = Drill diameter (mm)

Tab. 5: Power factor test matrix for drilling.

Speed (m/min)			Feed rate (mm/rev)	Depth (mm)
Brasses (all)	**12L14 steel**	**304L steel**		
152	122	38	0.13	38.1
305	244	76	0.18	-
457	-	-	0.25	-
610	-	-	0.38	-

In milling cuts, one or more cutting teeth are engaged in the workpiece at a time resulting in overlapping forces. A single indexable insert was therefore used in operation rather than a solid carbide cutter to ensure accuracy of measurement with the milling dynamometer.

Torque was measured by isolating the tangential force generated by a single insert while climb cutting. The lateral offset was set at 50% of the endmill diameter to generate a force which captures 100% of the chip load at the beginning of each cut. The insert exits the workpiece and repeats the cycle cut-by-cut, forming a sinewave pattern of dynamic force. A duty cycle of 0.25 (90°/360°) of the full rotation of the endmill is applied due to the interrupted cut. Under these conditions, power factor values for milling tests were derived and calculated based on peak tangential force combined with the average chip thickness as follows:

$$K = \frac{P}{Q} = \frac{Tc \times N \times \left(\frac{1W}{9.55x10^{-3}kW}\right)}{F \times N \times ae \times Dc \times \left(\frac{1cm^3}{1000mm^3}\right)}$$

when: $$Tc = Ft \times \left(\frac{D}{2000}\right) \times \left(\frac{hm}{F}\right)^2 \times .25$$

$$hm = F \times \sqrt{\frac{ae}{D}}$$

and: $$K = \frac{1.25\times10^{-4} \times ae \times Ft \times N \times \left(\frac{1}{9.55}\right)}{F \times N \times ae \times Dc \times \left(\frac{1}{1000}\right)}$$

reduced to: $$K = \frac{.0131 \times Ft}{Dc \times F}$$

K = Power factor ($W/cm^3/min$)
P = Power (W; in N·m/s)
Q = Metal removal rate (cm^3/min)
Tc = Torque, from avg. chip load (N·m)
N = RPM (rev/min)
F = Feed rate (mm/rev)
ae = Radial depth of cut (mm)
Dc = Depth of cut (mm)
Ft = Peak tangential force (N)
hm = Avg. chip thickness (mm)
D = End mill diameter (mm)

Power factor values for milling were calculated across all possible combinations of the parameters shown in Tab. 6.

Tab. 6: Power factor test matrix for milling (brasses only).

Speed (m/min)	Feed rate (mm/rev)	Radial depth of cut (mm)	Depth of cut (mm)
152	0.13	9.53	4.78
305	0.18	-	-
610	0.25	-	-
914	-	-	-

2.9 Surface roughness

Surface roughness (Ra, µm) was measured across a range of feed rates at mid-range cutting speeds in turning tests.

2.10 Chip formation

Representative chips formed from all materials during turning and drilling operations were collected, evaluated and classified in accordance with ISO 3865 first edition – 1977-05-15 which defines standard chip forms.

3 RESULTS

In some cases, data for the non-leaded alloys has been blinded to protect the competitive positions of the respective alloy suppliers. For power factor and surface roughness analyses, average minimum and maximum values measured for the three non-leaded alloys are shown to demonstrate general trends and to provide a meaningful machinability comparison to the other materials.

3.1 Turning

Speed limitations based on tool life

Four hour tool wear tests were performed at relatively low and high speeds on non-leaded brasses to determine if a carbide tool could be worn out in a reasonable timeframe. Comparisons were made at 914 m/min for high speed and 152 m/min for conventional speed (i.e. handbook recommendation). Tests were conducted at 0.08 mm/rev feed rate and 1.14 mm cutting depth. Tool wear was minimal (0.19 mm flank wear) after four hours at 914 m/min. Tool wear plotted against cutting time in Fig. 1 shows that the insert is still within the break-in period as seen by the plateau of the rate of tool wear.

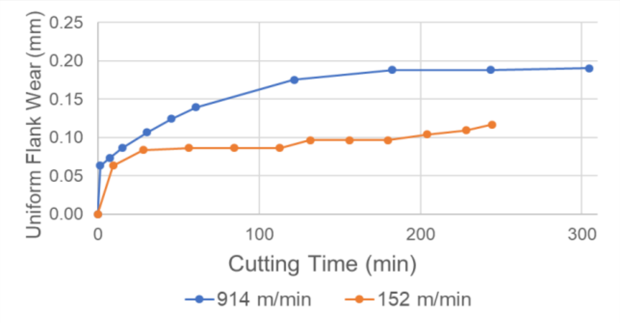


Fig. 1: Tool wear on C27450 vs. total cutting time.

From a standpoint of total productivity, the insert removed over 8,000 cm^3 of material at 914 m/min compared to 1,075 cm^3 at 152 m/min during the same period which translates to about a 7.4x increase in productivity as shown in Fig. 2.

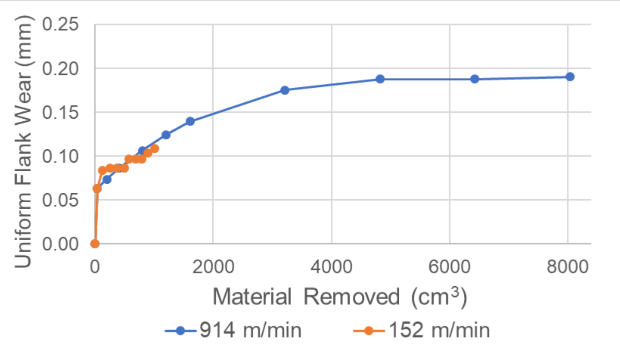


Fig. 2: Tool wear on C27450 vs. material removed after four hours of continuous turning.

Fig. 3 shows that a speed of 244 m/min for turning of 304L steel with a KC5010 grade insert resulted in an acceptable tool life of 31.8 min. For 12L14, the KC5010 grade resulted in 30.3 min. of tool life at 244 m/min while a K25P grade insert resulted in 31 min. of tool life at 366 m/min.

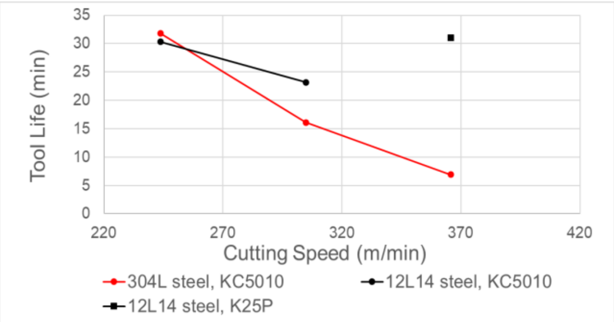


Fig. 3: Effect of speed on tool life for steels.

Fig. 4 shows measured flank wear and the condition of each insert at the end of the tool life tests.

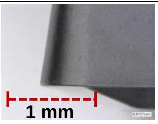
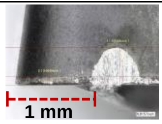
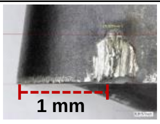
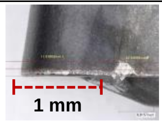
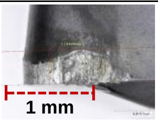
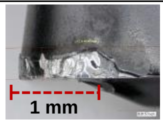
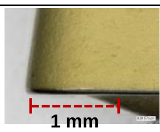
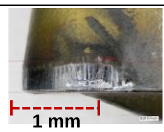
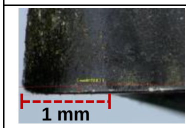
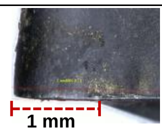
KC5010 Grade		KC5010 on 304L	
	New insert		6.9 min at 366 m/min
KC5010 on 304L		KC5010 on 304L	
	16.1 min at 305 m/min		31.8 min at 244 m/min
KC5010 on 12L14		KC5010 on 12L14	
	23.2 min at 305 m/min		30.3 min at 244 m/min
K25P Grade		K25P on 12L14	
	New insert		31.0 min at 366 m/min
KC5010 on C27450		KC5010 on C27450	
	60.0 min at 305 m/min		60.0 min at 914 m/min

Fig. 4: Representative tool wear on different inserts and materials across a range of speeds and cutting times.

Power factor

Fig. 5 shows power factor as a function of feed rate at a mid-range speed suited for each material. Power factor for all materials improved with increasing feed rate. Compared to the brasses, 12L14 and 304L steels required more power to turn and were evaluated at significantly reduced cutting speeds due to the practical restrictions on tool life.

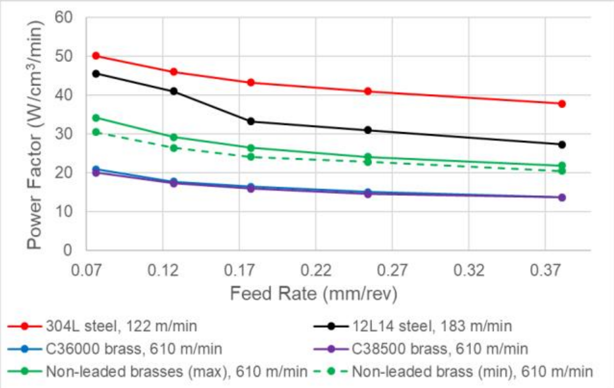


Fig. 5: Effect of feed rate on power factor at a mid-range speed and a depth of cut of 1.14 mm.

Fig. 6 displays power factor as a function of turning speed. Power factor for turning the steels and non-leaded brasses improved as speed increased. In contrast, power factor remained essentially constant for the two free-cutting brasses with increasing cutting speed.

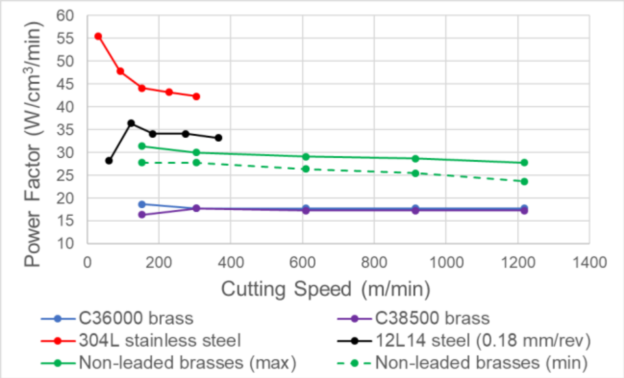


Fig. 6: Effect of speed on power factor at a mid-range feed rate (0.13 mm/rev) and depth of cut (1.14 mm).

Similar to feed rate, increasing depth of cut resulted in significant efficiency gains shown in Fig. 7 (brasses only).

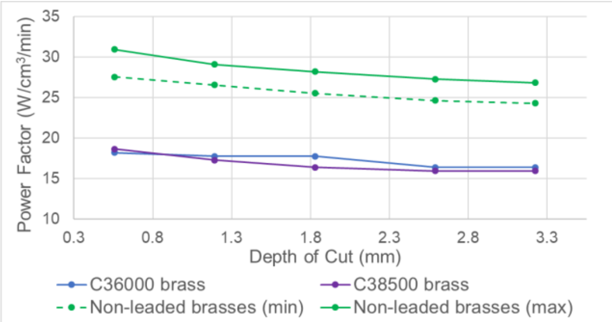


Fig. 7: Effect of depth of cut on power factor for brasses at 0.13 mm/rev feed rate and 610 m/min speed.

Surface roughness

Data for all materials is plotted in Fig. 8. at a cutting depth of 1.14 mm and mid-range speeds suited to each material to provide distribution curves expressing the effect of feed rate on surface roughness. In general, empirical data were consistent with theoretical roughness values for all alloys.

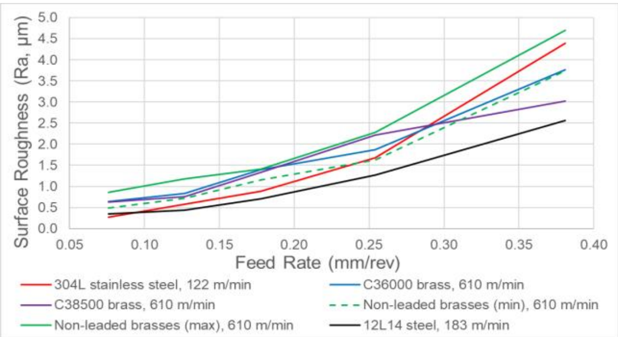


Fig. 8: Surface roughness (Ra, µm) with a 0.79 mm nose radius at mid-range speeds and 1.14 mm depth of cut.

Chip formation

Free-cutting brasses produced ideal class 7 elemental chips across most feed rates, speeds and depths. Occasionally, class 5.2 (short conical chips) and 5.1 (long conical chips) were produced at smaller feeds and lower depths of cut. Overall, both free-cutting alloys produced ideal chips across the complete range of feeds, speeds, and cutting depths. The non-leaded brasses performed best at feeds above 0.13 mm/rev with most chip forms comprising class 7 elemental and occasional short and long conical chips shown in Fig. 9. Longer chips were more frequent at smaller feeds with two occurrences of snarled chip forms at small feed rate and depth of cut combinations.

Fig. 9: Non-leaded brass chips across all speeds and depths. Top row shows >90% of chip forms by volume.

Most chips for 304L steel were of acceptable class 5.2 short conical shapes at feeds of 0.13 mm/rev or higher as shown in Fig. 10. There were some class 2.1 segments at feeds below 0.13 mm/rev which was expected for light finishing passes given the selected insert geometry.

Fig. 10: Representative turning chips, 304L stainless steel.

12L14 steel produced smaller elemental class 6.2 and 7 chip formations across all feeds as seen in Fig. 11.

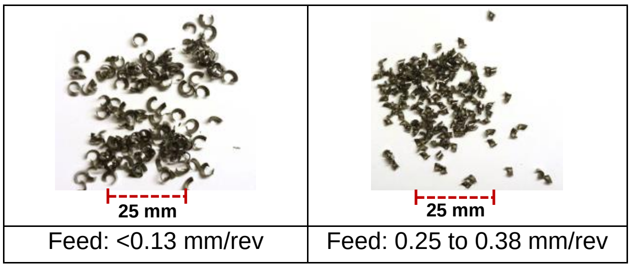


Fig. 11: Representative turning chips, 12L14 steel.

3.2 Drilling

Speed limitations based on tool life

Acceptable tool life was achieved with 304L steel (i.e. completed 1,000 holes) at a top speed of 76 m/min and 0.18 mm/rev feed. 12L14 steel exhibited a limit of 244 m/min at 0.25 mm/rev feed. At higher speeds, the drills chipped or fractured in both steels after fewer than 400 holes per Fig. 12. The tested brasses successfully completed 1,000 holes at a top speed of 610 m/min and 0.25 mm/rev feed with minimal tool wear, except for minor chipping on one flute.

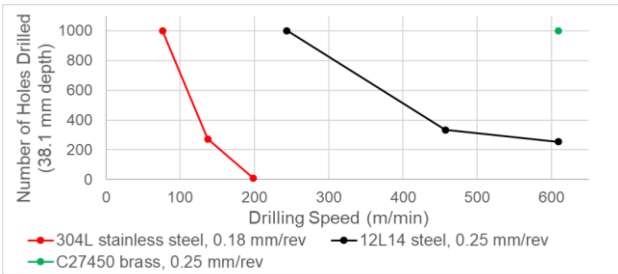


Fig. 12: Effect of speed on drill life.

Fig. 13 shows drill conditions at the end of each tool life test of 1,000 holes at 38.1 mm depth for 304L, 12L14 and a non-leaded brass. In all cases, the drills should be able to produce more than 1,000 holes at slower speeds since speed was optimized for all materials in the comparison.

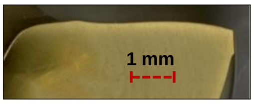
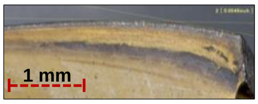
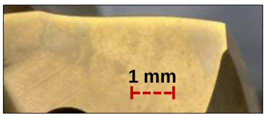
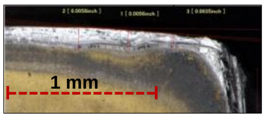
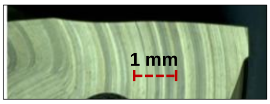
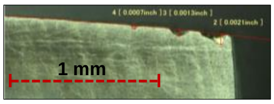
304L steel: New drill	1,000 holes in 304L (76 m/min; 0.18 mm/rev)
	
12L14 steel: New drill	1,000 holes in 12L14 (244 m/min; 0.25 mm/rev)
	
C27450 brass: New drill	1,000 holes in C27450 (610 m/min; 0.25 mm/rev)
	

Fig. 13: Tool wear from drilling at optimized speeds.

Power factor

Fig. 14 shows power factor as a function of feed rate for drilling across all tested materials at a fixed mid-range speed suited for each material based on the tool life testing. For 304L steel, power factor decreased significantly with increasing feed rate while 12L14 steel and the non-leaded brasses demonstrated slight gains in efficiency. Power factor for the free-cutting brasses was essentially constant.

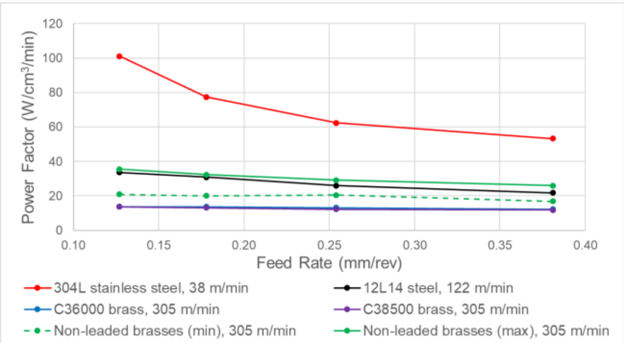


Fig. 14: Effect of drilling feed rate on power factor.

As only two speeds were tested for the steel alloys, there was insufficient data to examine the effect of drilling speed on power factor. The non-leaded brasses demonstrated slight efficiency gains with increasing speed while power factor for the free-cutting alloys was constant per Fig.15.

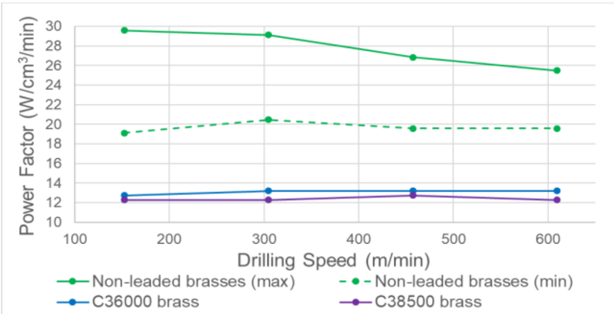


Fig. 15: Effect of speed on power factor at 0.25 mm/rev.

Chip formation

All brass chips were class 7 elemental and ideal for drilling at all combinations of speed and feed rate. Most chips for 12L14 steel were acceptable class 5.2 short conical shapes at a feed rate of 0.13 mm/rev, with loose class 6.2 and very short class 5.2 chips at 0.25 mm/rev per Fig. 16. 304L steel produced longer class 5.1 conical shapes at 0.13 mm/rev with class 6.2 chips at 0.25 mm/rev as seen in Fig 16.

12L14 steel small feed (0.13 mm/rev)	12L14 steel medium feed (0.25 mm/rev)
	
304L steel small feed (0.13 mm/rev)	304L steel medium feed (0.25 mm/rev)
	

Fig. 16: Representative drilling chips for tested steels.

3.3 Milling

Speed limitations based on tool life

Exploratory tests on non-leaded brasses revealed that insert life was too short for sustained production at 914 m/min. Thus, subsequent tests were run at 762 m/min which completed 120 min. of cutting with 0.03 mm of flank wear and minor chipping of the cutting edge per Fig. 17.

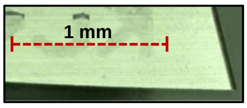
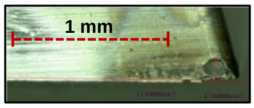
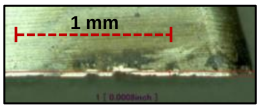
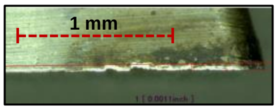
New insert	83 min. at 914 m/min and 0.13 mm/rev feed
	
60 min. at 762 m/min and 0.13 mm/rev feed	120 min. at 762 m/min and 0.13 mm/rev feed
	

Fig. 17: Flank wear on milling insert, non-leaded brass.

Power factor

Power factor for the non-leaded brasses was generally higher than the free-cutting alloys as seen in Fig. 18. Power factors for milling were lowest between 305 and 610 m/min. Milling was also most efficient at higher feed rates for the free-cutting brasses (up to 25% at 0.25 vs. 0.13 mm/rev).

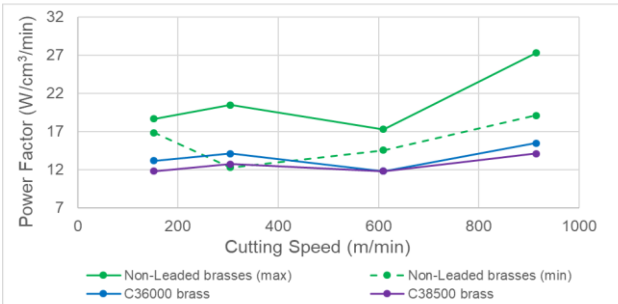


Fig. 18: Effect of speed on power factor at 0.25 mm/rev.

3.4 Industrial case study

To complement the laboratory tests, a case study was designed to assess the productivity gains that could be readily achieved with brass via high speed machining on a representative commercial part shown in Fig. 19. Two eight hour shifts of continuous production were performed on a twin-spindle Nomura DS NN-32UB8 CNC Swiss lathe with an 8,000 RPM main spindle and a 6,000 RPM sub-spindle. The lathe was equipped with a bar feeder, indexable carbide inserts and oil cutting fluid. The part was made from C27450 brass bar stock in 31.8 mm diameter. The first production run employed conventional parameters recommended in machining handbooks. The optimized run applied higher speeds, feeds and depths of cut derived from the laboratory tool life tests with the goal of approaching the maximum productivity conditions permitted by the machine. A before and after comparison of metal removal rates and cutting speeds for optimized operations is shown in Tab. 7.

Fig. 19: Case study part.

Tab. 7: Metal removal rate and cutting speed comparison.

Operation	Conventional	High speed	Gain
OD groove and cutoff	16.4 cm^3/min	55.7 cm^3/min	240%
	152 m/min	623 m/min	309%
Rough / finish bore	39.3 cm^3/min	100.0 cm^3/min	154%
	152 m/min	624 m/min	310%
Rough / finish groove	22.9 cm^3/min	55.7 cm^3/min	143%
	152 m/min	552 m/min	263%
Rough drill	122.9 cm^3/min	211.4 cm^3/min	72%
	152 m/min	349 m/min	129%
Rough / finish OD	1.6 cm^3/min	6.6 cm^3/min	300%
	152 m/min	457 m/min	200%

Tool wear was almost nonexistent after the high speed run, resulting in little measurable effect on dimensional growth. Chip forms were mostly acceptable, with occasional long chips observed from turning, threading and grooving. The result was a 38.5% productivity increase shown in Tab. 8.

Tab. 8: Productivity at conventional vs. high speeds.

	Cycle time (sec)	Parts per 8 hours
Conventional	52	553
High speed	32	900

4 DISCUSSION

The results establish basic machinability data and the rationale behind exploring the effects of speed, feed rate and depth of cut over a range that is considered conventional to high speed machining. The data show that both free-cutting and non-leaded brass can be machined at extremely high speeds for practical production periods with minimal tool wear. In general, higher metal removal rates did not negatively impact chip formation or surface integrity. Further gains for all materials could likely be realized by applying standard methods for optimizing tool geometry and carbide grades [Fernández-Valdivielso 2016].

While the non-leaded brasses generally required more power than the free-cutting alloys, efficiency improved significantly under high speed conditions. Thus, some machining challenges associated with non-leaded brasses could be mitigated on faster and more powerful machines. The case study revealed that an eight hour shift of continuous production of brass parts was successfully completed on a single set of tools at the maximum permissible speeds on a modern machine tool. Due to limited signs of tool wear, the life-limiting factor of tool performance is likely chipping caused by chatter or excessive heat buildup. Care should be taken to minimize tool deflection under increased loads at higher speeds.

It is apparent from the above data that brass can be machined at much higher rates than 12L14 and 304L steels with significantly longer tool life. In addition, the power requirements for brasses are considerably less. As such, manufacturers must consider the combined cost of decreased tool life, more rapid tool wear and its effect on dimensional control, and throughput when considering steel over brass. Taken collectively, the findings suggest that recommended machining parameters for brasses are often overly conservative. Of course, implementation of higher machining rates will depend on numerous factors, not the least of which is machine tool capability. While not fully optimized, the results herein provide a reasonable starting point for most situations. Manufacturers should consider the value proposition for high speed machining when contemplating the return on investment for modern machine tools. From a design perspective, engineers should evaluate high speed machining capabilities and the impact on per part cost and lead time when specifying materials.

5 SUMMARY

The productivity upside manufacturers can achieve with brass on advanced machine tools was amply demonstrated through a robust testing regime in laboratory and production settings. High speed machining of brass has been shown to yield impressive productivity gains with little penalty in tool life. To take full advantage of the high speed machining potential of brass rod alloys, advanced cutting tools must be used on equipment with the latest capabilities.

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