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MACHINABILITY CHARACTERISTICS OF Cu-Sn WORK-PIECE MATERIALS: AN EXPERIMENTAL STUDY

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Abstract
This paper presents the results of (single point turning) tests. The latter were carried out in order to examine the cutting stability of different lathe/cutting tool/bell-material-specimens at a feed rate of 0.35mm/rev, depths of cut of 1, 2, 3mm, and variable cutting speeds of 63 and 90 rpm. The work-piece specimens were 3cm and 10cm in diameter and length, respectively. They were prepared by casting into both clay molds and green sand molds with compositions of bell material and forming mixtures being similar to that used for making bells in Modern and Recent eras. The machinability characteristics evaluated in this study involved the cutting force components in tangential, radial and axial directions. Also examined were any significant changes in the machined surface roughness (Ra) and the length and morphology of chips. The particular intention of these experiments was focused on finding and selection of the optimum cutting conditions for tuning a larger bell using the horizontal industrial lathe.

Key words: turning tests, bronze materials, machinability characteristics, cutting forces, machining power, machined surface roughness, chip morphology.

1. INTRODUCTION

Different type Cu-Sn bronzes [1 to 7] are common materials used for casting bells. The bells are designed to sound at a particular level and tone [2, 6 and 7]. These performance characteristics depend on designing [2, 6 and 7], casting [1, 2, 6 and 7] and tuning [1, 5, 6,and 7] approaches. The older traditional methods used by different bell makers over centuries were recently described in literature sources [1 to 7] and as such are not repeated in this paper. However, an approach to tuning the bells using a lathe machining system is briefly shown below, because this relate closely to the topic selected for this paper *i.e.* experimental study of metal machining characteristics of different type bell materials.

The level and note of a bell depends on both the actual bell weight and the bell diameter at its 'mouth' [2, 3, 6 and 7]. These two variables are crucial in designing other geometrical parameters associated with the bell height, internal and external curves as well as the thickness distribution along the bell walls [2, 3, 6 and 7]. Although the bell design features can be calculated quite precisely for a particular bell to ring in its required note, the casting process itself has some peculiarities (caused on solidification and subsequent geometrical changes via metal shrinkage. Because of this the bell is usually designed to a slightly higher note than required and after casting it needs to be tuned down to the required note. In ancient eras the tuning was done manually by chipping the materials from the bell mouth along its lips, changing such vibrations and hence the lowering the sound to the level required for a particular note. Later this type of tuning was replaced with machining. Figure 1 shows a sketch describing principles used in tuning the bells to different tone (a), via metal removal from the internal parts of the bell (b).

It should be added that the objects such as bells should be machined at low cutting speeds and feeds, with relatively high depths of cut. From published results [8] it is evident that an approximation model based on a linear programming method determines, in fact, the amount of metal to be removed to so-tune a bell; however, there has been no discussion about the optimum machining process parameters (cutting speed, feed rate and depths of cut used), nor about the associated magnitudes and amplitudes in the cutting force components created while so-turning/tuning the bell. This information appears to be critical to determine the stability and the state of the object during lathe operations, and may also help to indirectly monitor machinability factors relating to the nature and composition of particular tin bronzes.

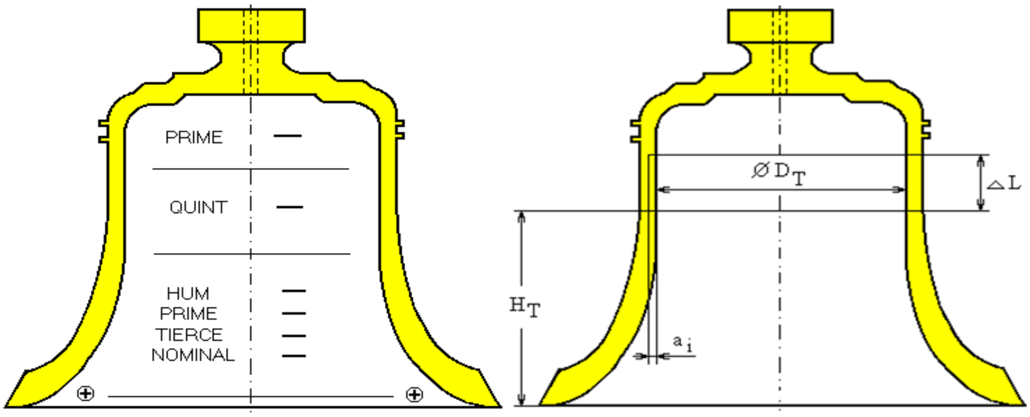


Figure 1. A sketch showing principles of tuning the bells to different tone (a), and the tuning parts of the larger bell (b), Adopted from source [6].

It also has to be concluded however that experimental cutting conditions may not be optimal for each bell. The actual approximate cutting speed depends, *inter alia*, on the diameter of the item to be machined, so the inter-dependence of phenomena developed in a particular process must be investigated, and the real time state of the cutting must be tracked individually, bell by bell. Optimization control of the cutting/tuning process parameters therefore appears to be critically important.

2. EXPERIMENTAL DETAILS

A set of preliminary machining (single point turning) tests was carried out in order to examine the cutting stability of a lathe/cutting tool/bell-material-sample system. Machinability characteristics of various tin bronzes were evaluated by measuring cutting force components in tangential, radial and axial directions and examining any significant changes in the surface roughness (Ra) and the length and morphology of chips. The particular intention of these experiments was focused on finding and selecting the optimum cutting conditions for tuning a larger bell using the horizontal industrial lathe.

2.1. Work-piece materials

For investigating machinability of various tin bronze morphologies via frequency analysis of the cutting force components, a set of specimens in a bar form was cast into a specially prepared forming mixtures according to procedures used in Modern and Recent Eras [6], as shown in Figure 2.

The Modern and Recent era like mixtures were similar to those used for casting into clay molds and casting into green sand molds [6, 7]. The alloy compositions (elements and their weight) are given in Table 1.

Figure 2. A photograph showing casting different type Cu-Sn specimens in a bar form for metal machining tests [6].

Table 1.Chemical composition of bronze specimens prepared for metal machining tests, [6].

Specimen type	Composition in wt %							Era (forming mixture)
	Sn	Pb	Zn	Sb	Fe	P	Cu	
I.	20	0.3	0.1	0.2	0.3	--	balance	modern (clay mold)
II.	20.25	1.5	1	1	0.25	1	balance	recent (green mold)

Specimens for machining were cut to 3cm in diameter and 10cm in length to achieve their actual size. After this, a tread of length of about 20mm was cut at one side of each specimen, by means of which the specimen was connected to a bar and maintained in the lathe chuck.

2.2. Turning Machine

The machining and turning experiments were carried out using an HMT lathe-Type L22PP. This horizontal turning machine had a power of 9.3KW, and was equipped with automatic longitudinal feed rates in the range of 0.062 to 1.41mm/rev, and variable speed spindle covering the range of 32 to 1400rpm. The distance between centers was 1000mm, and the maximum diameter of the work-material to be hold in the four jaws chuck was 450 mm [9, 10].

2.3. Cutting Tools

Turning-Machining experiments were carried out using a TiN+Ti (C, N) double layer coated carbide insert-Type TNMG160408QM215, mounted in a holder-Type MTJNR2525M16MI. The chemical composition, hardness and mechanical properties of this WC-based cemented cutting insert are given in Table 2, while properties of hard coating materials TiC and TiN are reported in Table 3.

Table 2. Chemical composition, hardness and mechanical properties of WC- based cemented carbide cutting inserts selected for cutting experiments [6].

Composition wt in [%] WC-TiC-TaC-Co (ISO Code)	Grain size (μm)	Density (g/cm^3)	Hardness (HR)	Transverse rupture strength (MPa)	Compressive strength (MPa)	Modulus of rigidity (GPa)
72-10-10-8 P20-TX20	1-2	12.2	91.5	2.000	4.800	540

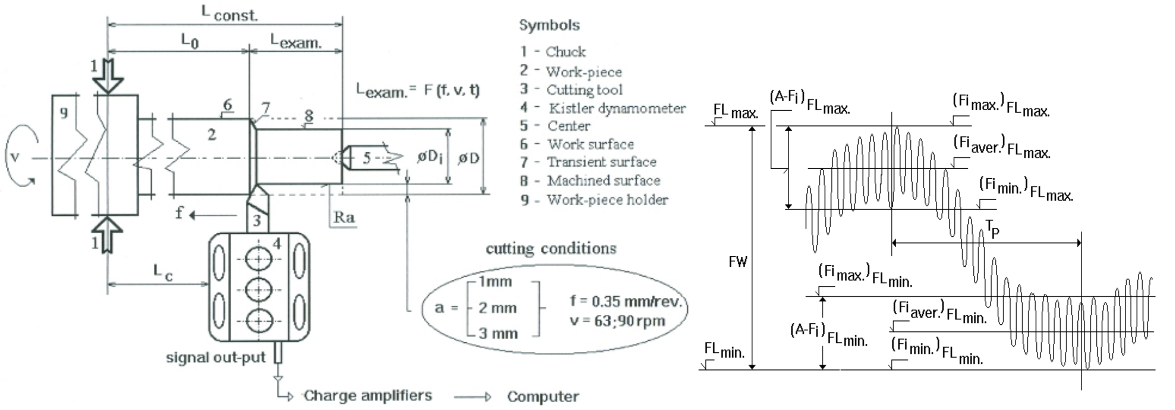
Table 3. Properties of hard materials used as coatings [6]

Material	Melting point °C	Density g/cm^3	Hardness HV	Coefficient of thermal expansion $10^{-6}/K$	Thermal conductivity W/mK
TiC	3150	4.94	3000	7.7	29
TiN	2950	5.44	2100	9.4	19

This type of cutting inserts was chosen to perform the cutting tests, because of its ability to produce no tool wear and no built-up edge is a short time machining period [10]. Thus it is expected that frequency charts relating to the cutting force components obtained in this way will reflect only vibrations relating to the machinability of different bronze samples to be examined and frequency data will be free of interfere signals. Machining experiments were carried out under standard cutting conditions [11 and 12]. The approach angle κ_r was set up to 90° as recommended by the handbook [13].

3. MONITORING OF MACHINABILITY OF TIN BRONZES BY MEASUREMENT OF CUTTING PROCESS PARAMETERS

Within these experiments, the dependence of amplitudes and magnitudes (AFz,y,z) of cutting force components (Fx, Fy and Fz) on the composition and microstructure of various commercial tin bronze bars was investigated. Cutting experiments were carried out using double coated carbide tools. Bronze samples were machined at variable cutting speeds (v) of 63 and 90 rpm, feed rate (f) of 0.35 mm/rev, and depths of cut (a) of 3, 2 and 1 mm. Some of experiments were repeated two times to verify the repeatability and accuracy of the measurements. The effect of cutting conditions was investigated in relation to the machined surface roughness (Ra) and cutting force components (Fi, i=x, y, z) and their amplitudes (AFi, i=x, y, z). Dynamic characteristics produced by the cutting system were recorded with a Kistler dynamometer, and evaluated at ten seconds intervals, with measurements being made at the sampling rate of 250Hz. The conditions of the experimental set up including the approach used to analyze the cutting force magnitudes are drawn in Figure 3 (a) and (b), respectively.



(a) (b)

Figure 3. Key elements (forces and amplitudes) to frequency analysis of the dynamic characteristics obtained while machining tin bronzes – bell material [6, 10, 14]. Where the symbol FW represents the width of a frequency signal; Fi correspond to Fx, Fy and Fz cutting force components; Fi_{max} and $_{FLmin.}$ Associate with the maximum values of cutting force components (Fi - x, y and z) measured in the minimum level of the frequency chart.

The Kistler dynamometer-Model 9257B was used to carry out the test experiments y recording the amplitudes and magnitudes associated with the cutting force components. The natural frequency of this piezocrystal three component dynamometer was 2KHz. Based on the Kistler company information, the stiffness of piezocrystal elements was 800, 800 and 2000N/μm for the load applied in the x, y, and z directions, respectively [14]. The out put signal from the dynamometer was carried by a special insulated cable-Type 1687B5 to the three charge amplifiers-Model 5011, and force signals were analysed using an IBM PC computer equipped with a PCL-718A/D card, and Snap Master Programme [15].

More detailed information about this type of measurements, its accuracy and data analyses associated with the forces and amplitudes occurring in metal machining processes can be found in literature source [16].

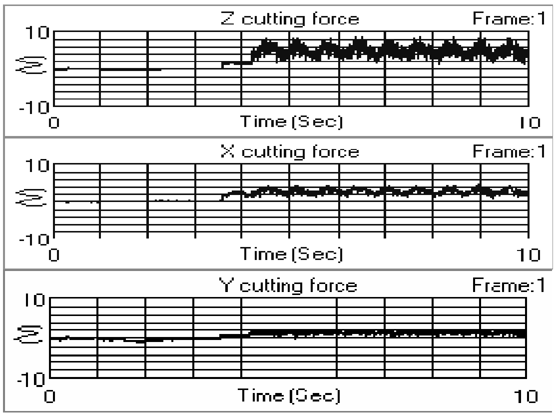


Figure 4. An example of experimental plot for Fz, Fy and Fx cutting force components obtained from bronze sample (II.), machined at a constant cutting speed of 90 rpm, feed rate of 0.34mm/rev, and depth of cut of 1mm by using a TiN+Ti(C, N) coated carbide insert - Type TNMG 160408QM 215 impounded in a Type 2525M16M1 holder. The overhang of the tool holder was 2 cm. The scale of measurement (0-10 V) is equal to 0-1000 N for Fz, Fy and Fx.

4. RESULTS

The force out-puts were used to examine differences in the machinability factors of different tin bronzes. One original frequency chart, as measured, is included as an example, in Figure 4. Voltage out-put/time graphs were here presented (1) giving the overall variation with significant dumping over the 10 seconds cutting interval, and (2) in detail over three successive time intervals within this overall time frame.

4.1. Cutting Force Components

Figure 5 usefully summarize all of the cutting force data and shows the force trends obtained for these different tin bronze '*bar*' work/materials Type I and II (for the experimental design parameters) in the form of maximum, minimum and averaged values of the resultant force (Fr) and its three components (Fx, Fy and Fz).

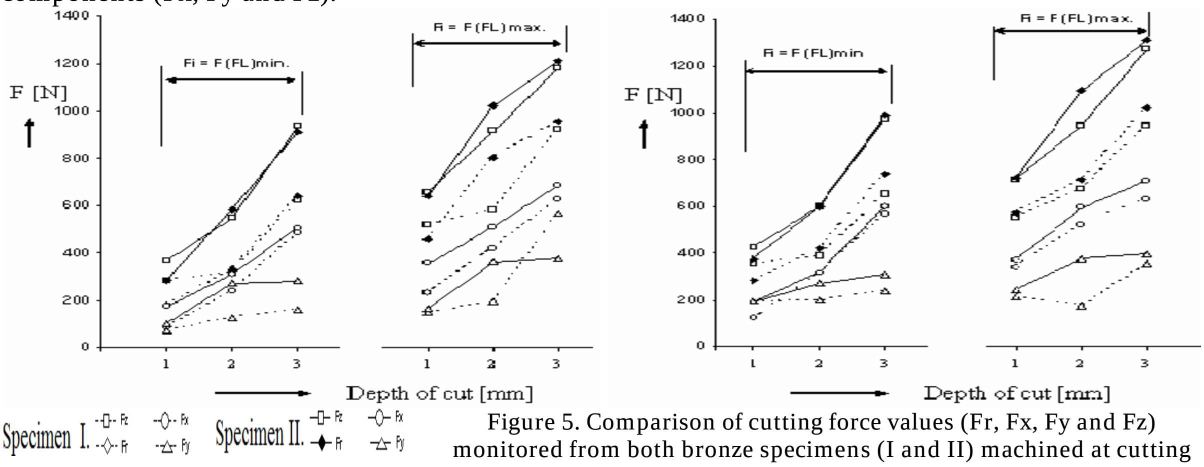


Figure 5. Comparison of cutting force values (Fr, Fx, Fy and Fz) monitored from both bronze specimens (I and II) machined at cutting speeds of 63 rpm (a) and 90 rpm (b), a feed rate of 0.35 mm/rev, and depths of cut of 1, 2 and 3 mm.

These data were calculated from the lowest and highest levels in the frequency zone (as shown earlier in Figure 3 (b), and indicates the significant differences in the cutting force components, in the z, x and y directions, values decreasing in the order z>x>y, with the z component being substantially larger than the x and y components. The Fr values and associated cutting force components (Fx, Fy and Fz) obtained from specimen II were, in balance, larger than those observed from specimen I. Such differences become more significant as the cutting speed decreased and depth of cut increased.

4.2. Surface Roughness Measurement and Chip Morphology

The measured and calculated surface roughness values of the machined surfaces of all two bell materials I and II are presented in Table 4 for both test conditions used.

Table 4. Machined surface roughness of experimental Type I and II bell material specimens

Cutting Conditions			Specimen I		Specimen II	
Feed Rate [mm/min]	Cutting Speed [rpm]	Depth of Cut [mm]	Ra [µm]			
			Average	St. dev.	Average	St. dev.
0.35	63	1	5.3	0.058	4.9	0.100
		2	5.1	0.058	4.9	0.058
		3	5.4	0.058	4.7	0.265
0.35	90	1	4.8	0.100	4.4	0.100
		2	4.7	0.058	4.5	0.058
		3	4.9	0.058	4.6	0.058

The photograph in Figure 6 shows the changes in the length and morphology of chips/swarf produced with the Type I and II bronze samples machined under the experimental cutting conditions.

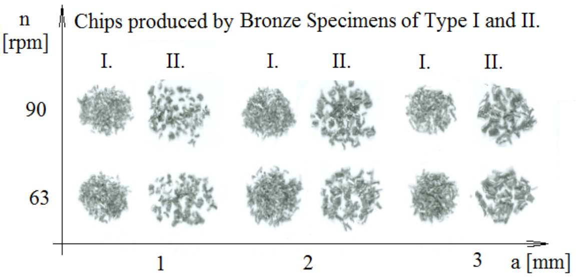


Figure 6. Comparison of chips produced by the Type I and II bronze specimens [6]

5. DISCUSSION

Without the built-up edge effects and with properly adjusted cutting conditions the resultant cutting force (Fr) and all its three constituents (Fx, Fy and Fz) increased with the values of depths of cut. Also amplitudes and magnitudes of the cutting force components increased with the cutting speed and depths of cut. The tangential force reflected the cutting power and its value was several times higher that that of axial (Fx) and radial (Fy) cutting components. The feed force (Fx) was found to be closely linked to the chip morphology, while axial force (Fy) was found to be sensitive enough to reflect the bending effect of a particular work-piece. The comparison of experimental trends indicated that there may be some relationship between dynamic characteristics and metallurgical features of the bronze specimens I and II. Figure 5, for example, has been derived by superposing force trends for specimens I and II. This figure concerns and contrasts the machinability behavior between the two bell material samples in a bar form cut now with reference to the chemical composition of these samples. Here it becomes clear that there are differences, chemical composition by chemical composition, structure features by structure features and all these differences become clear and more evident as the cutting speeds and depths of cut are increased. The cutting forces obtained from the specimen I were much lower than those measured from the specimen II, depending on the chemical composition and hence influenced by the actual microstructure of alpha phase – copper and (α+δ) eutectoid dictating such differences in the hardness of the experimental specimens. The specimen I was much softer than specimen II. For the specimen I the microhardness $HV_{0.002}$ data of the α phase and (α+δ) eutectoid were 144.5 and 182, respectively. For the specimen II it was 228 and 321, for the α phase and (α+δ) eutectoid, respectively. The comparable differences between the dynamic variables (Fz, Fy, Fx and Fr) increased with the cutting speed and depths of cut.

The effect of fundamental parameters of the L-T-W cutting system and the cutting conditions on the machined topography of bells was investigated from machining tests. The Ra values produced by Sample I varied in the range of about 4.7 to 5.3 µm, while for Sample II it was of 4.4 to 4.9 µm. This compares well with the recommended surface roughness Ra produced at conditions similar to rough machining which is around 6.3 µm. For both cutting conditions (v=63 and 90rpm) the Sample II produced better roughness than Sample I, what, it is believed, associated with the higher amount of lead and phosphorus in Sample II than in Sample I making Sample II to produce elemental chips while needle chips were produced by the Sample I. These experiments also confirmed that the values of Ra decreased with the increase in the cutting speed.

6. CONCLUSIONS

Principal conclusions derived from observations associated with the turning process are as follows:

- The similarity of frequency chart records indicated very good repeatability of the measurements and sensitivity of Kistler measuring technique on the variations in dynamic characteristics produced by the L-T-W cutting system chosen to perform the cutting experiments.
- The amplitude period of the frequency characteristics relating to the cutting force components increased with the cutting speed. The average values of the resultant forces determined from the

highest and lowest levels of the frequency charts slightly decreased as cutting speed increased, and increased with the increase in the depths of cut. Variations in the cutting force components reflected variations in the homogeneity of a given work-material sample machined. The Fr values and associated cutting force components (Fx, Fy and Fz) obtained from sample II were, in balance, larger than those observed from sample I. Such differences become more significant as the cutting speed decreased and depth of cut increased

- In the range of cutting conditions used, the tin bronze alloys (Type I and II) produced short elemental chips with their size and morphology depending on the hardness of a particular work-material sample machined indicating good machinability of both types of tin bronzes examined.
- The numerical values of the machined work-material roughnesses varied of ~5 to 5.4μm and of 4.7 to 4.9μm for the specimen I machined at cutting speeds of 63rpm and 90rpm, respectively. For the specimen II it was of ~4.9 and of ~4.6μm while machining at speeds of 63rpm and 90rpm, respectively. All the Ra values were in the range recommended by industrial standard for a given set of cutting conditions.
- The dynamic frequency signals of cutting forces and their amplitudes correlated very well with the changes in the chip morphology and the Ra values.

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