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Machinability characteristics of lead free-silicon brass alloys as correlated with microstructure and mechanical properties

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Machined surface roughness

Abstract The aim of this work is to evaluate the machinability of Pb-free brasses with Si from 1% to 4 wt%, which were prepared using Cu 60/Zn 40 and Cu 80/Si 20 Pb-free master alloys. Machinability of the investigated alloys is tested based on cutting force, tool wear, surface roughness, and chip type. In the 1 wt% Si alloy, which exhibits maximum strength, the maximum cutting force is measured and undesirable continuous chip type is produced, while tool wear and machined surface roughness have the lowest values. Increasing the silicon content from 1% to 4%, results in increasing the tool wear by 140%, machined surface roughness by 25%, while the chip type changed from continuous to discontinuous type, and the cutting force was reduced by 50%. Machinability results are correlated with the alloy mechanical properties and with the phases present in the microstructure.

1. Introduction

Copper and copper alloys can be divided with respect to machinability into three groups, namely highly machinable (free-cutting), moderately machinable, and difficult to machine alloys [1]. The machinability of copper and copper alloys is improved by lead, sulfur, tellurium, and zinc while it deteriorates when tin and iron are added [2]. Lead in brass alloys with concentrations around 2 wt%, improves machinability by acting as a microscopic chip breaker, and tool lubricant, while they increase the brittleness of the alloy [2]. Similarly, sulfur and tellurium are added to copper in small amounts for machinability

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improvements [3]. The addition of Zn up to the limit of solubility (about 37% Zn) increases hardness of ά-brass.

Lead in the alloy is present on the surface of the alloy and thus presents a health concern similar to that of pure lead. The growing environmental concerns have increased the demand for Pb-Free brass at various industries.

Development of easily machinable Pb-free brass has been considered by a number of researchers [4–6], where Pb was replaced by Bi, and Se. Also other elements such as phosphorous and indium can be added in small amounts for this purpose to the alloy [7–9]. In Pb-free brasses, increase in zinc content from 0% to 30% improves the machinability rating from 20 to 30. Further increase in zinc content beyond the solubility limit shows more machinability improvement. Silicon has been also considered to replace Pb [10,11].

The present work is concerned with the effect of replacing Pb by Si up to 4 wt%. Data on cast microstructure and phases formed and the mechanical properties of these alloys are reported by the authors elsewhere [11,12]. The purpose of the present work is to study the machinability of these Pb-free brasses with Si up to 4% and 0.5 wt% Al. The machinability is evaluated by the cutting force, tool wear, surface roughness and chip type and is correlated to the metallurgical phases identified in the specimen microstructure.

2. Experimental work

2.1. Material

The alloys under investigation have been prepared by gradually adding a copper–silicon master alloy (80% Cu–20% Si) into a prepared and molten Cu 60/Zn 40 brass master alloy superheated to 1200 °C. Both alloys are Pb-free ones and are high purity prepared using cathodic Cu. The chemical compositions of the Si brass alloys prepared are given in Table 1. The table also gives the chemical composition of the Pb-free master Cu 60/Zn 40 alloy used for their preparation and the leaded brass alloy C37700, as a reference for comparison. The prepared alloys were poured in low carbon steel mold to cast cylindrical shaped ingot 33 mm in diameter and 130 mm long. The cooling rate of the castings (measured by K-type thermocouple 0.8 mm in diameter which was inserted in the casting middle) was 35 K/min with a scatter range of 5 K/min. More details on the alloys preparation are reported by the authors elsewhere [11,12].

2.2. Machinability test

Machinability test was conducted using a conventional center lathe with eight rotational speeds ranging from 32 to 1000 rpm, and feeds ranging from 0.063 to 0.64 mm/rev. Machinability specimens were fixed in a special holder between chuck and center, which ensures specimen stability, and accuracy of machinability results. Each machinability measurement was taken as average of three samples, with a scatter range of 5%. The cutting force (F_c) was measured using a dynamometer connected to a strain gauge mounted on the corresponding cutting tool surface. Fig. 1 shows specimen holder, test specimen, and a sketch for the test arrangement respectively''.

Machinability test parameters included cutting tool material and geometry. For this purpose, two types of thread turning tools were used with cemented carbide tips; namely H123 having a positive rake angle and H20 having a negative rake angle. Their tool angles are given in Table 2. Three groups of experiments were conducted in order to study the effect of cutting speed (v), feed (mm/rev), and depth of cut (a) on machinability ratings. Table 3 illustrates the selected cutting conditions applied.

Machinability is evaluated based on four machinability criteria; namely cutting force measurements, tool wear measurements, surface roughness measurements, and type of chip produced [13–15]. Machinability based on cutting force measurements was established by measuring the main cutting force (F_c) using a cutting force dynamometer. For machinability based on tool wear, a 2 min pre-selected machining time was set [16]. The wear on the tool flank was measured using optical tool room microscope, by measuring the thickness of worn layer. For machinability based on surface roughness, the average surface roughness (R_a) was measured using surface roughness tester type MITUTOYO surf Test 301. Chips produced using both cutting tools, at the different cutting conditions were collected, photographed and classified in a tabulated form.

3. Results and discussion

3.1. Microstructure and mechanical properties

The microstructure of cast Pb-free Si brass alloys is shown in Fig. 2a. Depending on Si content, several phases were detected by X-ray analysis made on disk specimens 15.5 mm diameter and 2 mm thick indicates the formation of these phases. As shown in Fig. 2b, the phases are α, β, γ, λ, η, and χ. The phases appeared with different volume fraction (measured microscopically under different magnifications using the grid method).

The variation of mechanical properties (ultimate tensile strength, elongation% and hardness) with Si content is shown in Fig. 3. The results indicate that adding Si up to 1 wt% leads to β phase formation and decrease of α phase, as shown in Fig. 2b. This results in increasing both ultimate tensile strength

Table 1 Chemical composition (EDX Analysis) of Pb-free Si brasses investigated, Pb-free master alloy and the reference leaded brass.

Element	Cu	Pb	Fe	Si	Al	S	Sn	Zn
Alloy 1 (1% Si)	60.2	0.005	0.032	1.11	0.445	0.003	0.001	Rest
Alloy 2 (2% Si)	60.1	0.003	0.127	1.92	0.55	0.009	0.001	Rest
Alloy 3 (3% Si)	60.4	0.003	0.081	2.89	0.489	0.005	0.013	Rest
Alloy 4 (4% Si)	60.2	0.003	0.074	3.94	0.498	0.004	0.001	Rest
Master alloy 60Cu/40Zn	60.92	<0.001	<0.001	<0.001	<0.001		0.0052	Rest
Reference Leaded Brass Alloy (C37700)	Rest	1.947	0.217	0.002	0.047		0.195	39.5

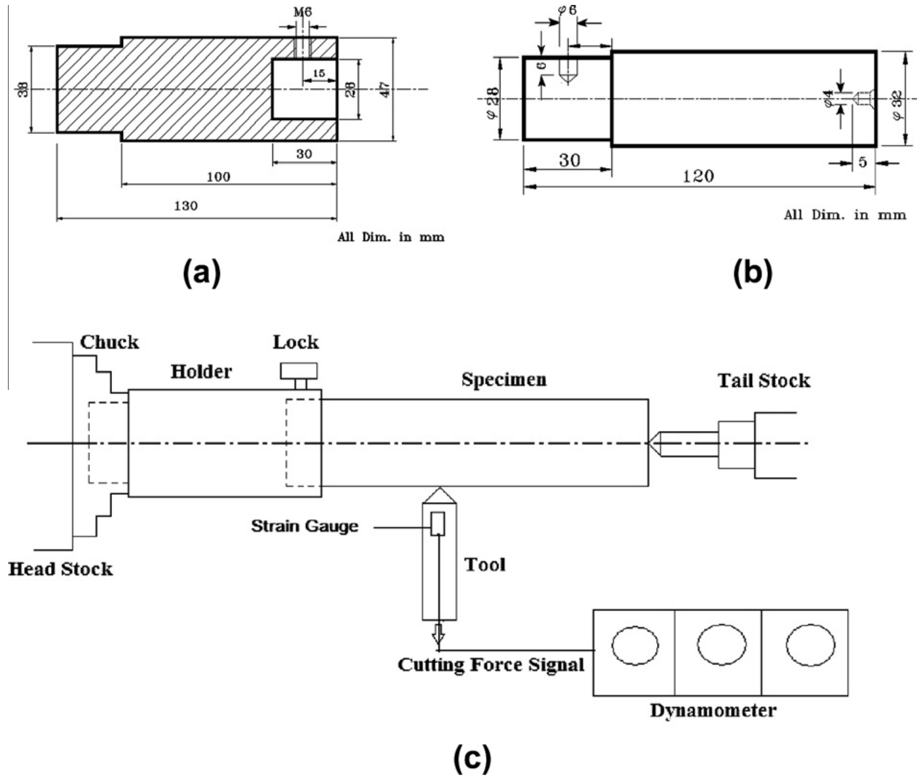


Figure 1 Machinability test: (a) specimen holder, (b) specimen, and (c) sketch for the test arrangement.

Table 2 Tool angles of cutting tools used for machinability testing.

Tool Type	α (°)	γ (°)	æ (°)	æ$_1$ (°)	r (mm)
H123	12	10	60	60	Sharp
H20	13	−10	60	60	0.4

α = Clearance angle, æ = primary approach angle, r = nose radius, γ = rake angle, æ$_1$ = secondary approach angle.

and hardness and in decreasing ductility, Fig. 3. With more Si addition up to 4 wt%, the volume fraction of β phase rapidly decreases and α phase remains with constant volume fraction while brittle phase's γ, λ, η, and χ are formed. This results in decreasing strength and ductility. More details are reported and discussed by the authors elsewhere [11,12].

3.2. Machinability index

A machinability index rating is commonly used to rank the different alloys based on their relative ease of cutting [13,14]. The leaded brass (C37700) which is a free machinable brass is considered the reference alloy with 100% Machinability Index. Different machinability indices are defined. Based on cutting force, relative force rating index RFRI, is calculated by dividing the cutting force for the reference leaded brass under certain cutting conditions by that of Pb-free Si brass alloy. Similarly, other indices based on tool wear (relative tool wear rating index, RTRI), and surface roughness (relative roughness rating index, RRRI) are also calculated. The chip type formed is also considered for machinability evaluation, referring to standard chip type classification [1,15]. Based on chip type, relative chip type rating index (RCRI) is calculated by dividing the chip type rank for the Pb-free Si brass alloy under certain cutting conditions by that of the reference leaded brass.

3.3. Machinability based on cutting force

The effect of different parameters on the cutting force is found similar for both H123 and H20 tools. Fig. 4 shows that for all leaded and unleaded alloys, the cutting force (F_c) is proportional to the depth of cut. Fig. 5 shows a similar relationship between cutting force and cutting feed. In both cases, the behavior can be attributed to increased resistance of chip formation as a result of the increase of the volume of the undeformed layer. Fig. 6 indicates that the cutting force increases

Table 3 Cutting conditions used in machinability testing.

No.	Objective	Cutting speed (v) (m/min)	Feed (s) (mm/rev)	Depth of cut (a) (mm)
01	Effect of cutting speed	Variable: 22.6–41.5–65.8 104	Constant at 0.08	Constant at 0.5
02	Effect of feed	Constant at 104	Variable: 0.08–0.14–0.2	Constant at 0.5
03	Effect of depth of cut	Constant at 104	Constant at 0.08	Variable: 0.5–0.75–1

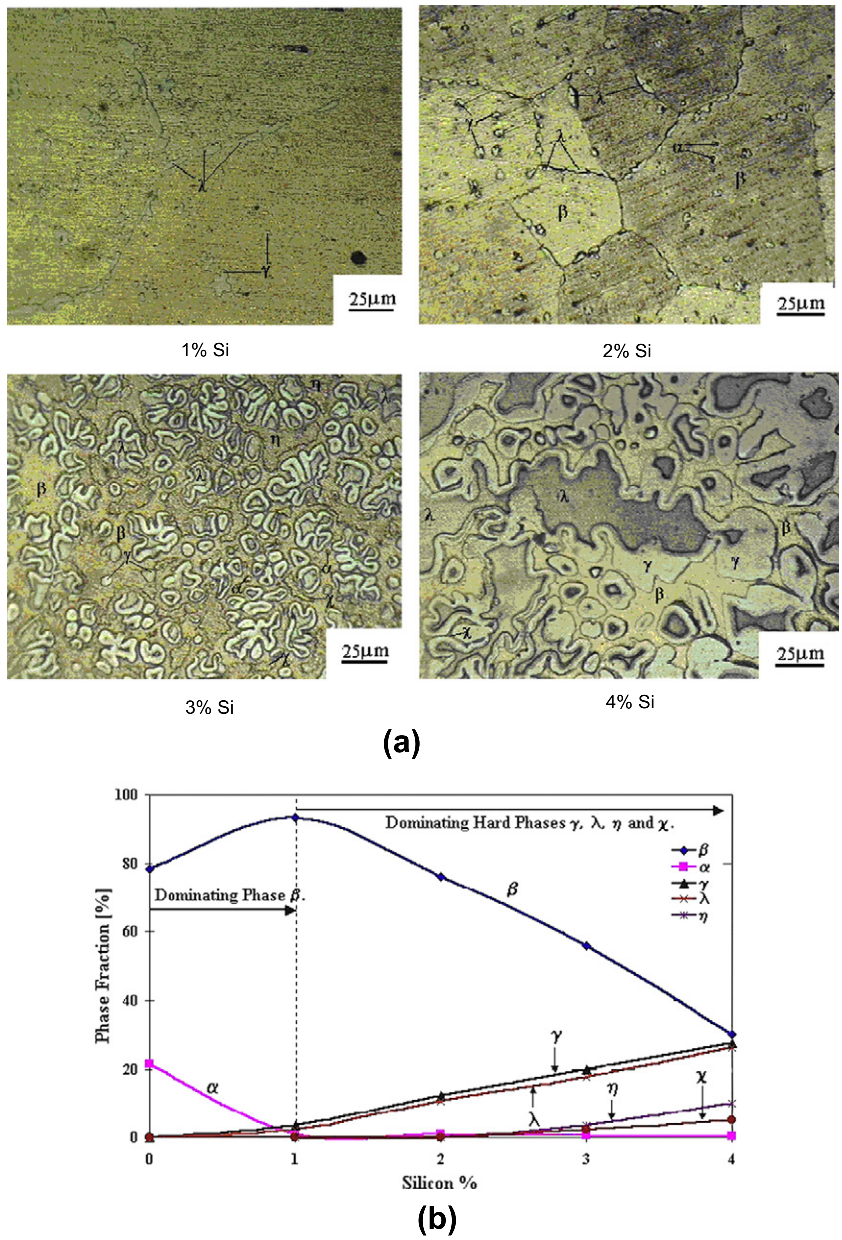


Figure 2 Variation of the microstructure of cast Pb-free Si brass alloys with Si content up to 4 wt%: (a) micrographs indicating phases and their locations and (b) variation of phase's volume fraction with Si content.

with increasing cutting speed up to a maximum at 50 m/min. This is due to the increase of friction on the tool face caused by the movement of chip flow with speed. With further increase in speed, cutting force decreases, which can be attributed to increase of the cutting temperature at such high speeds, resulting in decreasing the friction forces between chip and tool face [17]. Generally, leaded brass gave the lowest cutting force value due to the reduction of the coefficient of friction between the chip and the tool face caused by the lubricating effect of lead [2]. The maximum cutting force measured at 1% Si can be attributed to the highest alloy strength. The behavior is similar to previous work on other alloys [18].

For both tools H20 and H123, the effects of Si content on measured cutting force and calculated ‘‘relative force rating index’’ RFRI are shown in Fig. 7a and b respectively. The two relationships are opposite to each other, with an inflection point existing at 1% Si. RFRI decreased from a maximum (between 70% and 80%) for the unleaded Cu60/Zn40 brass to a minimum (between 40% and 55%) for 1 wt% Si alloy. Further increase in Si wt% resulted in increasing RFRI up to a value between 64% and 68% at 4 wt% Si.

Machinability results in Fig. 7 are correlated with microstructural phases and alloys strength referring to Figs. 2 and 3. As Si% increased (from 0% to 1% Si), α phase decreased and the dominating β phase increased, which leads to rapid increase in strength. Further increase in Si% up to 4% Si led to the formation of brittle hard phases λ, η, and χ, which resulted in a gradual decrease in strength. Therefore, the cutting force and the RFRI showed a similar behavior due to the combined effect of alloy hardness and strength.

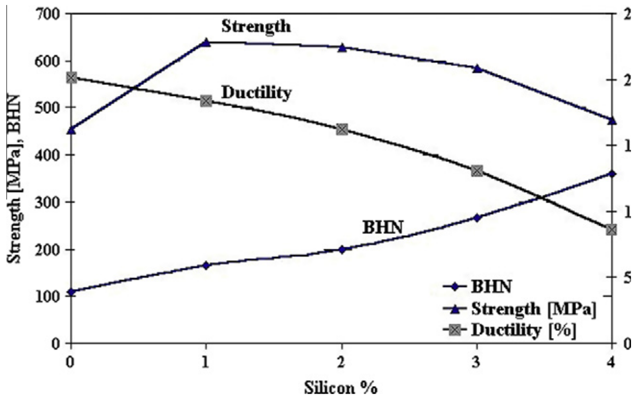


Figure 3 Variation of mechanical properties of cast Pb-free Si brass alloys with Si content up to 4 wt%: ultimate tensile strength, ductility (elongation%) and hardness BHN).

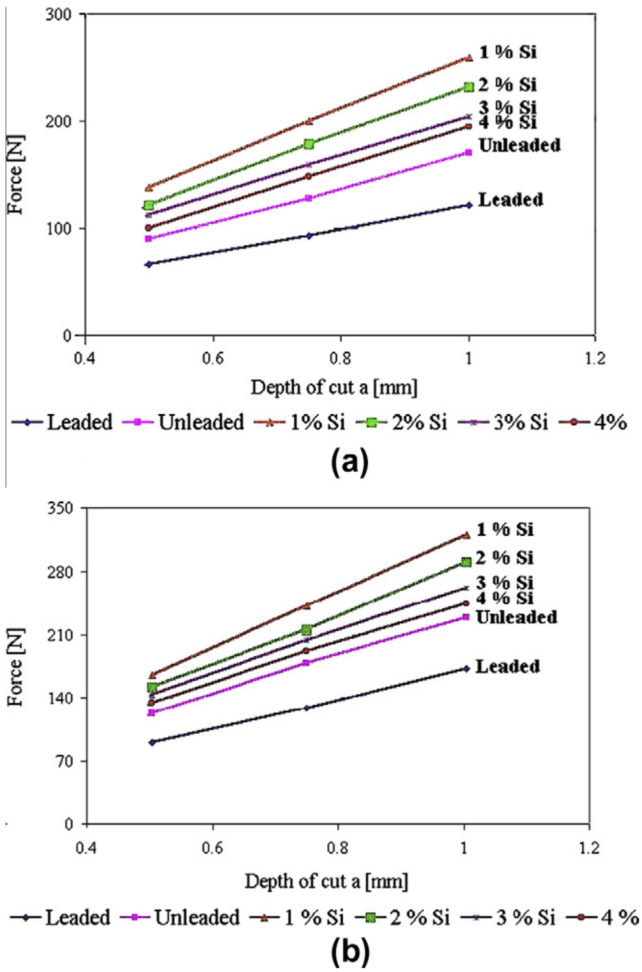


Figure 4 Effect of depth of cut on cutting force for the cast Pb-free Si brass alloys with different Si content up to 4 wt% (constant feed of 0.08 mm/rev and speed of 104 m/min): (a) tool H123 and (b) tool H20.

Oishi [19] reported that, the measured cutting forces ranged between 118 N and 134 N for alloys with chemical composition range (2–4% Si, 69–79% Cu, and balance of Zinc),

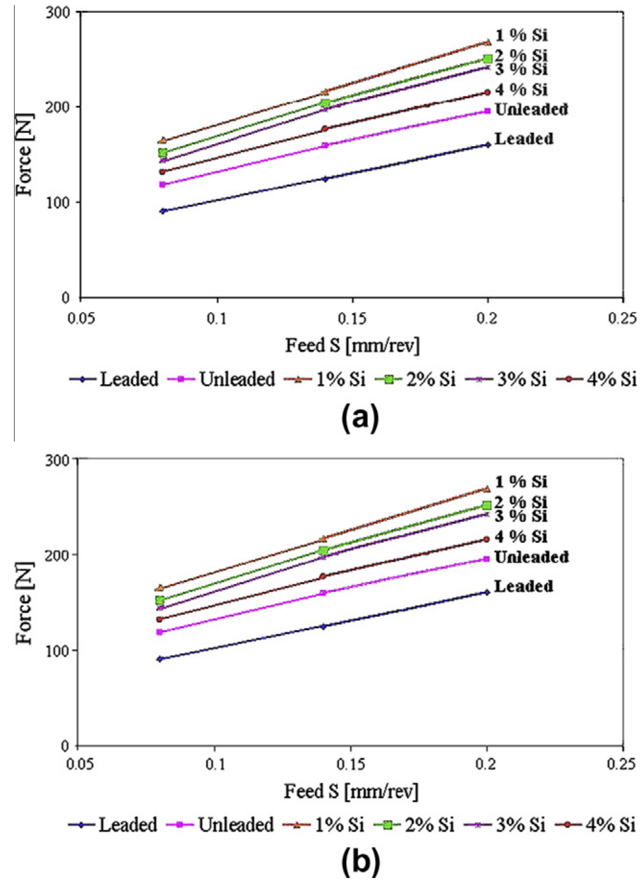
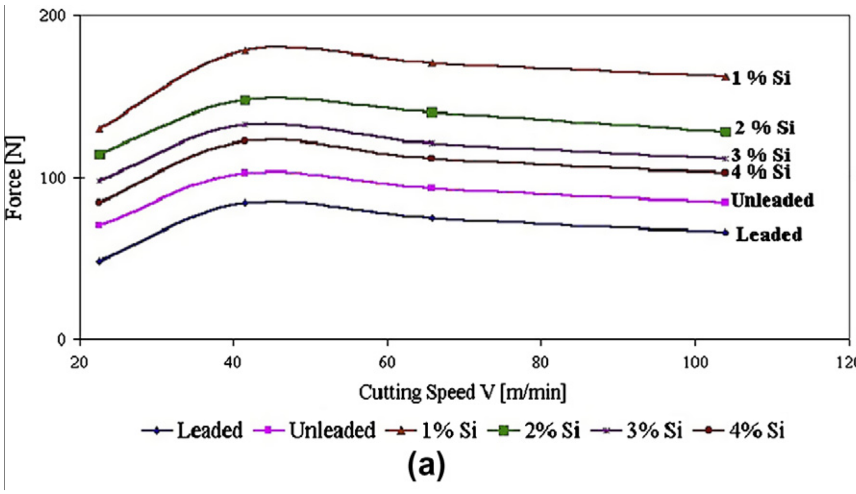


Figure 5 Effect of cutting feed on the cutting force for the cast Pb-free Si brass alloys with different Si content up to 4 wt% (constant depth of cut of 0.5 mm and cutting speed of 104 m/min): (a) tool H123 and (b) tool H20.

negative rake angle (−8°) turning tool was used at (a = 1.5 mm, s = 0.11 mm/rev, and v = 50 m/min) cutting conditions. The same researcher used the standard leaded brass (2% Pb) alloy as a reference alloy where the cutting force at the corresponding cutting conditions was 112 N. As reported [19], lower cutting forces and their corresponding high [RFRI] are due to the effect of increasing silicon content and corresponding structure variation. In the same reference [19], further machinability improvement was achieved by subjecting the brass to hot extrusion followed by heat treatment at (450–580 °C) for (20 min–4 h). By this way, the structure was modified to restrict the β phase to less than 5%, and to increase the total volume fraction of (λ, η, and χ,) phases above 30%, and additionally to keep α phase to above 30% [19]. Comparing both results on Si brass alloys of the as-cast alloys of the present work and the extruded – heat treated alloys of Oishi [19], Fig. 7b shows that the as-cast Si brass alloys exhibit lower machinability indicated lower RFRI than the extruded alloys.

3.4. Machinability based on tool wear

The tool wear of both tools H123 and H20 is investigated at selected cutting conditions. Fig. 8 shows the effect of Si content on average tool wear measured and the calculated "relative tool wear rating index" RTRI with Si wt%. The figure



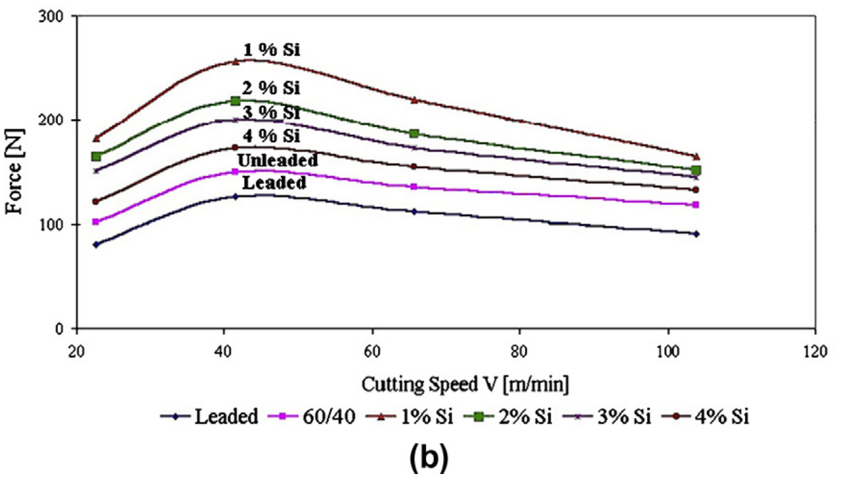


Figure 6 Effect of cutting speed the cutting force for the cast Pb-free Si brass alloys with different Si content up to 4 wt% (constant depth of cut of 0.5 mm and feed of 0.08 mm/rev): (a) tool H123 and (b) tool H20.

includes the results on both tools H20 and H123 at the selected cutting conditions (v = 70 m/min, s = 0.08 mm/rev, and a = 0.5 mm) for a machining time (t = 2.8 min). Fig. 8a shows that only a negligible amount of tool wear occurred during cutting the leaded brass, while the Pb-free brass has higher tool wear which increases with increasing Si wt%. The figure also shows that tool wear values for tool H20 are smaller than the values obtained for tool H123. This can be attributed to the combined effect of higher hardness, and larger nose radius of the H20 tool.

The wear results in Fig. 8 are correlated with microstructural phases and alloys strength referring to Figs. 2 and 3. As the Si wt% increases (from 0% to 1% Si) tool wear slightly increases, which is referred to the decrease of the softer phase α, and increase of the harder phase β. Oishi [19] reported that, in silicon brass alloys, there is a harmful effect of β phase on tool wear. Further increase in silicon content (from 1% to 4% Si) led to further moderate increase in tool wear due to the formation and increase in volume fraction of hard phases λ, η, and χ. Tool H20 exhibited less wear rate than tool H123 due to its high hardness and larger nose radius, which resulted in an almost linear relationship between tool wear and silicon content. As the silicon content was increased (from 0% to 4% Si), the tool wear gradually increased with no significant effect of hardness and microstructure changes.

Generally, a decreased relative tool wear rating index [RTRI] was calculated for both tools as a result of increasing the Si wt%. By comparing Figs. 7b and 8b, the contradicting effects of Si content are recognized as positive effect on [RFRI] and negative effect on [RTRI]. This effect is a direct result of the dependence of cutting force on alloy strength, and the dependence of tool wear on alloy hardness, which emphasizes the importance of considering both machinability measures. Referring to the relative improvement in [RTRI] by using tool H20, Fig. 8b, it can be concluded that, by selecting the suitable cutting tool with proper hardness and tool geometry, lower tool wear rates and economic tool life can be achieved during the machining of the examined silicon brass alloys.

3.5. Machinability based on surface roughness

The machinability based on machined surface quality is evaluated by measuring the machined average surface roughness (R_a) at selected cutting conditions using tool H20. The results are plotted in Fig. 9 for R_a versus depth of cut keeping the feed and speed at 0.08 mm/rev and 104 m/min respectively. The

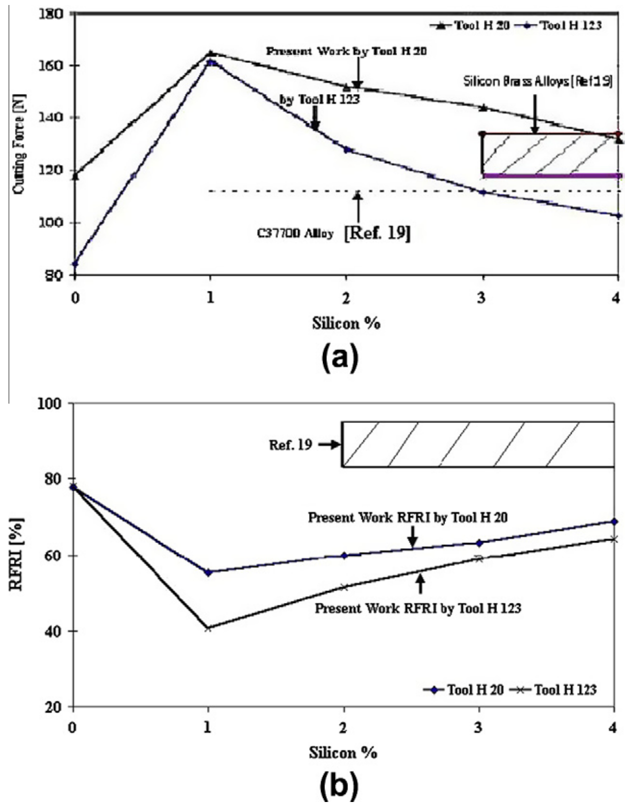


Figure 7 Effect of Si content on: (a) cutting force and (b) relative force rating index "RFRI". The figure includes the present results on cast Pb-free Si brass alloys up to 4 wt% previous results on similar alloys after hot extrusion followed by heat treatment [19].

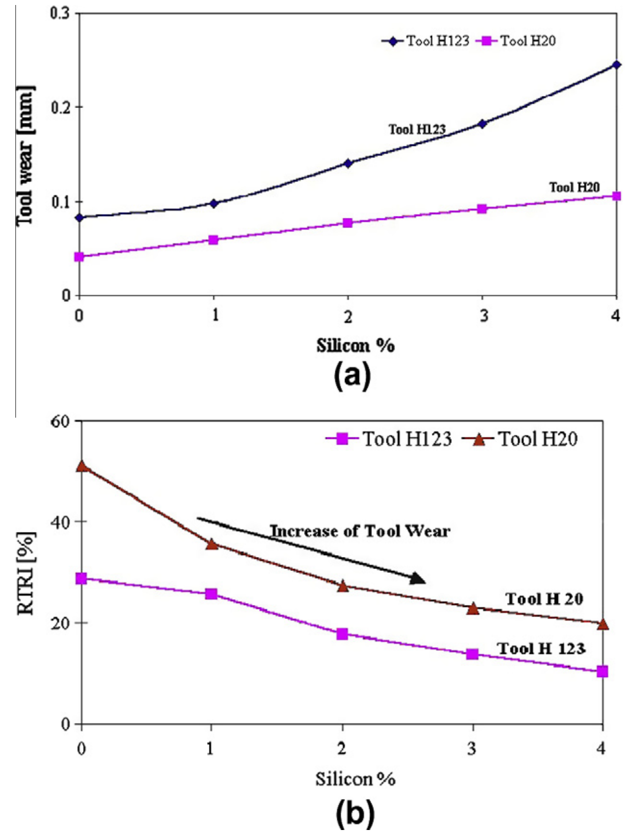


Figure 8 Effect of Si content in cast Pb-free Si brass alloys up to 4 wt% on: (a) average tool wear and (b) relative tool wear rating index "RTRI".

effect of cutting feed and cutting speed on R_a is illustrated in Figs. 10 and 11 respectively. From these figures it is found that for all Si brass alloys investigated, R_a is almost constant with varying depth of cut, while it increases as the cutting feed increases and gradually decreases as speed increases. Minimum values are indicated for leaded brass, followed by (1% Si.) and (2% Si.) alloys, then the unleaded brass. Higher surface roughness values are indicated for (3% Si.) and then (4% Si.) alloys, so that R_a increases by (40%) as the silicon content increases from 1 wt% to 4 wt% Si.

The effects of Si content on R_a and corresponding "relative machined surface roughness index; RRRI" are shown in Fig. 12a and b respectively. The two relationships are opposite to each other, with an inflection point existing at 1% Si, where R_a is minimum with a maximum RRRI. The maximum RRRI value, at 1% Si is 78%, compared to 72% for the unleaded Cu 60/Zn 40 brass, and 65% for 4% Si. Surface improvement at 1% Si can be referred to the slight decrease in ductility and increase in hardness. The sensible increase in RRRI with further increase in Si from 1% to 4% can be correlated with the formation of hard brittle phases λ, η, and χ, in a relatively softer matrix β phase, which can be gouged out during machining resulting in a rougher machined surface [15]. Comparing the results with those of previous work [19], the present alloys can be classified as with an excellent surface roughness, ranging from 0.5 to 1.5 μm.

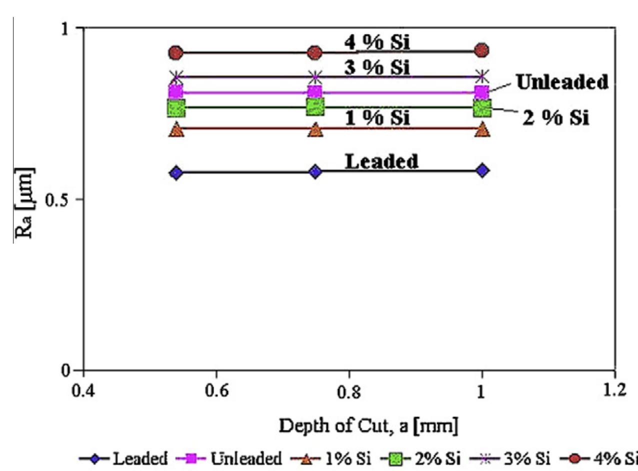


Figure 9 Variation of average machined surface roughness "R_a" of cast Pb-free Si brass alloys (Si up to 4 wt%) with depth of cut.

3.6. Machinability based on type of chip formation

The literature indicates that coded chip classification is possible based on the type of cutting chip formed [2,3,20,21]. Cutting chip type classification [15] includes undesirable long chip (types 1 and 2), followed by two passable long bevel and cylindrical long types (types 3 and 4), then three good

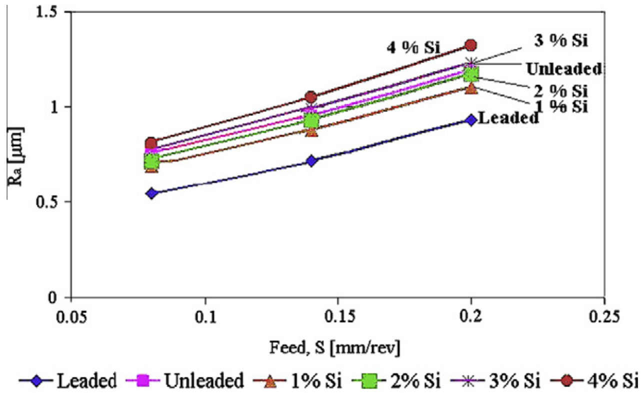


Figure 10 Variation of average machined surface roughness "R_a" of cast Pb-free Si brass alloys (Si up to 4 wt%) with feed of cut.

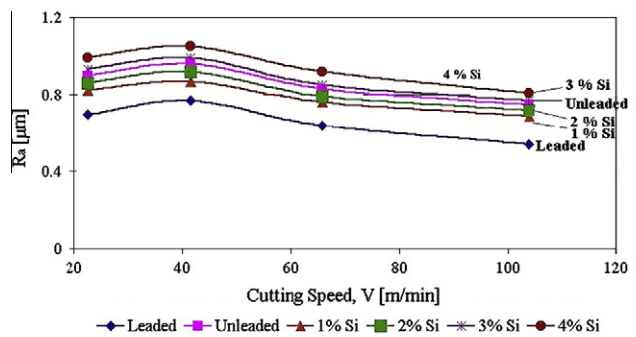


Figure 11 Variation of average machined surface roughness "R_a" of cast Pb-free Si brass alloys (Si up to 4 wt%) with cutting speed.

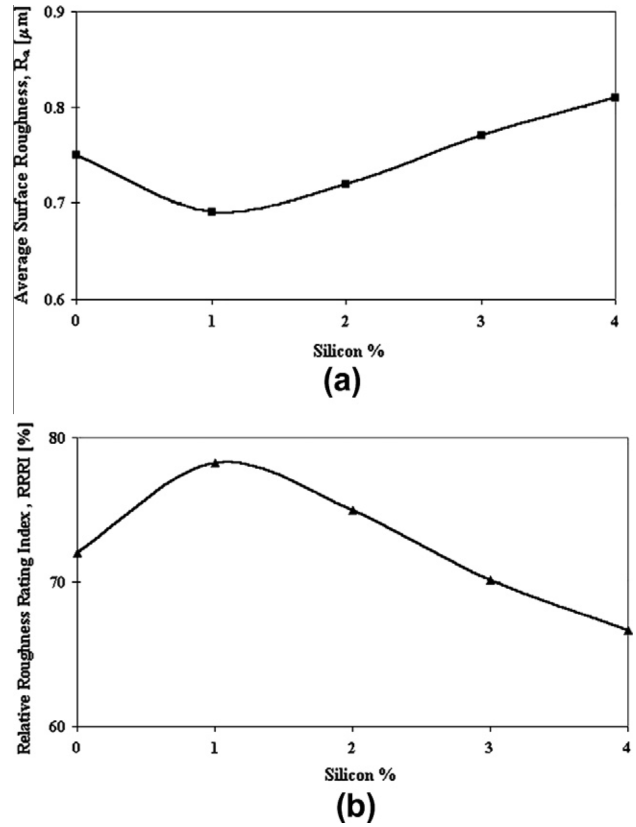


Figure 12 Effect of Si content in cast Pb-free Si brass alloys up to 4 wt% on: (a) surface roughness "R_a" and (b) relative machined surface roughness index "RRRI".

shorter chip types of (types 5, 6, 7 and 8), and at finally two excellent broken chip types (types 9 and 10). Based on this classification, the type of chip formed for the Si-brass investigated, under different cutting conditions of depth of cut (a), feed (s) and speed (v), for both tools H123 and H20, is defined as given in Table 4.

As the table indicates, within the investigated range of feed and depth of cut, there is no significant effect on the produced chip type for each alloy. However, varying cutting speed (v) has a significant effect where the chip changes from continuous to discontinuous type as the cutting speed decreases. It is to be noticed that decreasing v to achieve the desirable discontinuous chip type is not recommended due to lowering productivity.

The influence of Si content is also indicated in Table 4. By adding Si to the unleaded Cu 60/Zn 40 brass, the chip changes from the undesirable continuous type to passable long bevel and cylindrical long types. Excellent broken chip type is observed for 4% Si alloy.

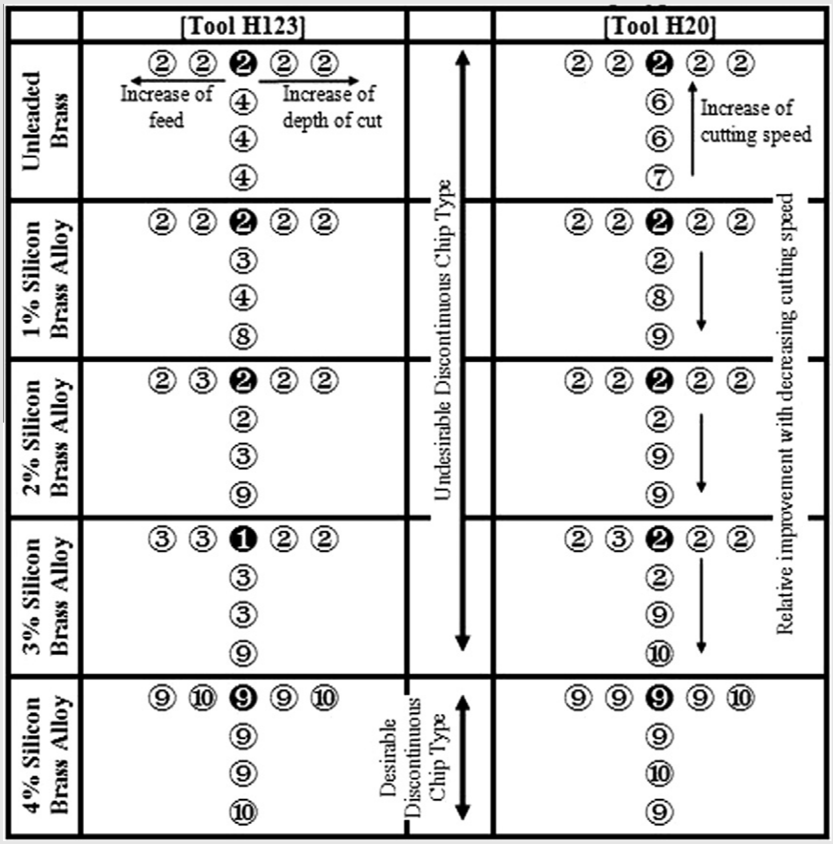
Fig. 13 relates the chip type formed with Si content. The results are considered in reference to microstructure and mechanical properties in Figs. 2 and 3 respectively. It is clear that the chip type is affected by the formation of hard precipitates rather than by the variation in mechanical properties. At 4% Si, hard λ phase became the microstructure – dominating phase, and the volume fraction of the hard and brittle phases η and χ reached nearly 25%, thus acting as chip breakers so that the chip became discontinuous. However, in case of 1% Si alloy, which exhibits the maximum mechanical properties, excellent chip type 9, was possible when using tool H20 at a lower cutting speed, as indicated in Table 4.

It is observed that the chip type produced has a remarkable effect on machined surface roughness (R_a). Due to changing chip type from continuous to discontinuous type, lowest R_a is found for leaded brass, followed by the alloys with 1 and 2 wt% Si then the Cu 60/Zn 40 brass and finally the 3 and 4 wt% Si alloys. The direct relationship between feed and surface roughness observed can be attributed to the formation of crack type discontinuous chip which leads to the increase of the machined surface roughness. As previously reported [13], the gained improvement in surface finish with increasing the cutting speed is due to better and easier flow of chip during machining, which results in reducing the machined surface roughness especially for the leaded brass.

4. Conclusions

Machinability results of Pb-free Si brass alloys with 1–4 wt% Si and 0.5% Al, are correlated with the alloy strength and with the phases present in the microstructure. The formation of β phase in the 1 wt% Si alloy resulted in maximum ultimate tensile strength, and hence maximum cutting force and lowest relative force rating machinability index "RFRI". For this alloy,

Table 4 Overall view of the produced chip types for investigated Pb-free Si brass alloys and base 60Cu/40Zn alloy.



1 and 2: undesirable long chip, 3 and 4: passable long bevel and cylindrical long types, 5, 6, 7 and 8: good shorter chip, 9, and 10: excellent broken chip.

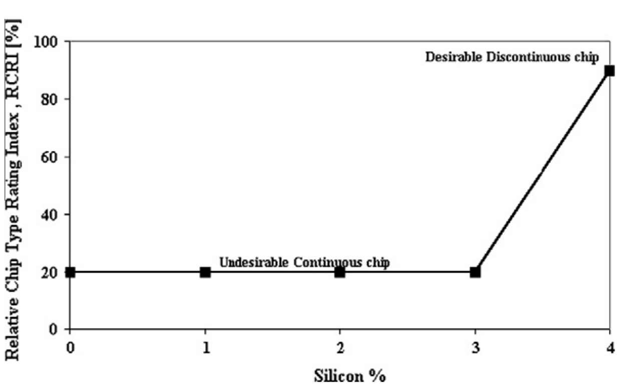


Figure 13 Effect of Silicon Content on chip type.

undesirable continuous chip type is produced, while it is highly ranked based on both relative tool wear machinability rating index "RTRI" and relative machined surface roughness index "RRRI" ratings. The formation of the brittle γ, λ, η, and χ phases results in reducing strength. In the 4 wt% Si alloy, discontinuous chip type is produced, while it is less ranked based on RTRI and RRRI ratings.

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