Investigation of machining performance of lead-free brass materials forged in different conditions after cooling with liquid nitrogen

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Abstract. The forging process, which is one of the hot forming methods, is used to produce plumbing systems, valves, batteries, fittings, condensers, pipes, etc. from brass alloys in duplex structures. Compared to leaded brasses, machining becomes very difficult due to reasons such as long and continuous chips, burrs, built-up edge in the tool, and unacceptable surface quality problems. In this study, studies have been carried out to improve the machining process that minimizes the mentioned machining problems by controlling the microstructural of lead-free brass materials. Therefore, by examining the effect of the copper content of the forged material, forging temperature, the cryogenic cooling method input parameters after forging on the phase ratio of the material, investigations were carried out on obtaining a high-performance machining process close to the machinability performance of leaded brass materials with good chip breakability. The change in the distribution of beta phases in the material after forging was investigated and machining tests were performed as a hole drilling operation. Cutting forces, surface roughness, and dimensional accuracy analyzes were evaluated within this purpose. The relationship between the beta phase ratio in the material and the machinability has been revealed and it has been observed that the CW511L alloy produced in three different ratios in the standard range and although they are the same material, the Cu% ratio causes significant changes in terms of machinability.

Introduction

Forging process is one of the widely used plastic deformation methods in terms of shaping the material. In this method, in which components from copper alloys are widely produced, the deformability of the billet material increases by heating it in the furnace and it is easily shaped. Zinc element in body-centered cubic crystal lattice structure, which is one of the elements that increase the forging ability. Brass is generally known as copper alloys containing 5% to 40% zinc in concentrations. While brass is manufactured, strength, corrosion resistance, machinability etc. Different alloying elements can be added to change the properties [1]. The most important element in this context is lead, which is associated with excellent chip breaking, low tool wear, and high cutting parameters. However, lead poses a danger to humans and nature and is included in the 2nd class carcinogen group, which cannot be eliminated by human body [2,3]. Pipes, fittings, etc., are produced from brass alloys, especially in contact with drinking water. The lead element ratio in the alloy in the components should not be more than 0.20%. CW511L material standard alloy ratios also support this [4]. In this study, the material that was shaped by hot forging and on which the machining tests were carried out is CW511L from lead-free brass materials. In the brass alloy, the semi-fluid lead layer reduces friction during cutting, acts as a lubricant, and encourages the formation of small discontinuous chips, improving machinability [5,6], cutting forces generated during machining, and thus cutting tool life are improved. The fact that lead is such an important element for machinability and its elimination causes various problems in terms of machinability in lead-free brass alloys and results in a decrease in productivity and disruption of processes with long chips and reduced tool life that occur during the processing of these materials [6].

Pantazopoulos et al. [7] investigated the microstructure analysis, mechanical behavior and fracture mechanisms of traditional leaded brass materials CuZn39Pb3 (CW614N) and CuZn36Pb2As (CW602N). It has been revealed in their studies that CW602N material with high copper content contains lower β phase compared to the other, has lower hardness, and decreases in toughness due to phase structure. Nobel et al. [6] examined and compared the machinability of lead-free alloys CW510L, CW511L, CW724R, CW508L and leaded alloys CW614N. After the machining of these materials by turning using carbide cutting tools were used in different coatings, temperature and force results investigations were carried out in terms of chip breakability, chip form and tool life. Toulfatzis et al. [8] evaluated the microstructures and β phase ratios of extruded cylindrical lead-free brass materials after heat treatment and looked at the impact of these outputs on the material's machinability in their study. In a different investigation [9], they used heat treatment to lead-free brass alloys to explore the chip breakability, the change in β phase following this heat treatment, and the machining test that followed. The fracture energy and fatigue life of lead-free brass alloy (CW510L and CW511L) materials as determined by the material's notch impact test were examined by Pantazopoulos et al. [10]. The drilling process of hot forged lead-free brass alloys was investigated experimentally by Zoghipour et al. [11] using a form cutting tool. The cutting forces, dimensional accuracy, and surface quality of the holes were tested while taking into account the tools' varied geometries, feed rates, and rotating speeds on hot-forged lead-free brass alloys with different copper contents. Then, to predict and improve the machining process, they applied genetic algorithm-based optimization techniques and modeling of artificial neural networks.

It is anticipated that changes in the material's copper ratio in the Cu-Zn equilibrium diagram will have a significant impact on the material's forgeability and recrystallization temperature, as well as on its microstructural distribution, α and β phase distribution, and consequently its machinability performance. After being hot forged into the desired shape, the brass alloy material is cooled either on its own or in fan conveyor systems, depending on the desired microstructural and mechanical qualities. There are several studies in the literature that demonstrate the use of the cryogenic cooling method in various operations for the machining of different materials [12–14], that it improves machinability performance [15], and that it has no negative effects on human health or the environment [16]. It is crucial to conduct systematic studies to enhance the machinability performance of lead-free brass materials because there are not any available studies examining the impact of forging parameters and cooling process on β phases in the material and the change in machinability performance as a result. In the study, a major breakthrough was made in terms of machinability since the β phases of the cryogenic cooling approach were restrained in the structure without dissolving with rapid cooling. Therefore, it has been attempted to investigate the effects of the forged material's copper content, the sample temperature prior to forging, the cryogenic cooling method input parameters following forging, and the material's phase ratio on achieving a high-performance machining process that is comparable to the machinability performance of materials containing lead. The microstructural characteristics of the material are significantly affected by forging process parameters including the material's percentage Cu alloy, the post-forging cooling technique, the forging temperatures, etc. These consequences have been shown along with this study. Several process characteristics, such as machinability, have a substantial impact on the β%, which are crucial in terms of machinability.

Experimental Setup

Hot forged extruded bars with dimensions of Ø50x66 mm and three different Cu% rates were put through machining testing. The shaped workpieces formed by the hot forging technique are shown in Fig. 1a. Before being employed in the machining experiments, Fig. 1b depicts the burr cutting procedure and the final shape shown in Fig. 1c. Based on the results of the spectral analysis, the chemical composition of the CW511L alloy material generated at three different Cu% ratios is shown in Table 1.

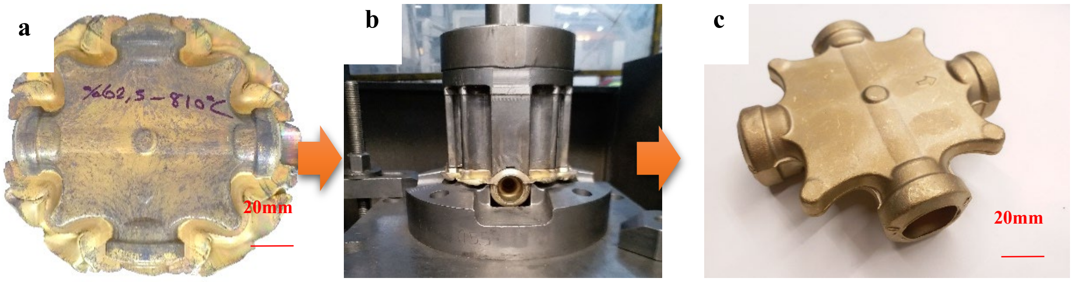

Fig. 1. a) Forged CW511L sample with burrs, b) burr cutting process c) final shape.

Table 1. Chemical composition of the CW511L material with different %Cu.

Material	Cu	Zn	Pb	As	Al	Sn	Ni	Bi	Si	Sb
%61.7 Cu	61.7	Rem.	0.181	0.106	0.003	0.00	0.000	0.003	0.011	0.004
%62.9 Cu	62.9	Rem.	0.174	0.117	0.003	0.00	0.001	0.003	0.002	0.003
%63.4 Cu	63.4	Rem.	0.164	0.106	0.003	0.00	0.002	0.003	0.006	0.002
EN12165 Standart [4]	61.5 63.5	Rem.	- 0.2	0.02 0.15	- 0.05	- 0.1	- 0.3	-	-	-

In a Hydromec-550 tons automated press, forging tests were performed. Forging temperatures of 750, 780 and 810°C were selected during the forging process. All test samples were subjected to a 1 minute cryogenic cooling process in a chamber made of 304L stainless steel, which has a low heat transfer coefficient and is resistant to cryogenic temperatures, after forging. This has been performed in order to apply the coolant (liquid nitrogen) to the component uniformly during cryogenic cooling. During this time, the test samples at forging temperatures between 750 and 810°C were cooled to an average temperature of 200°C. The machining tests were conducted on Fanuc-Robodrill α-D21MiB5 CNC machine as shown in Fig. 3. Boron coolant flood was used during the machining tests. Ø12 spherical carbide cutting tools were particularly made and utilized in the tests as part of the experimental investigation. A thermal camera was used to monitor this process for each sample. Table 2 provides the experiments specific conditions and parameters. Following the machining tests, the CMM was used to measure the dimensional accuracy in the hole diameters.

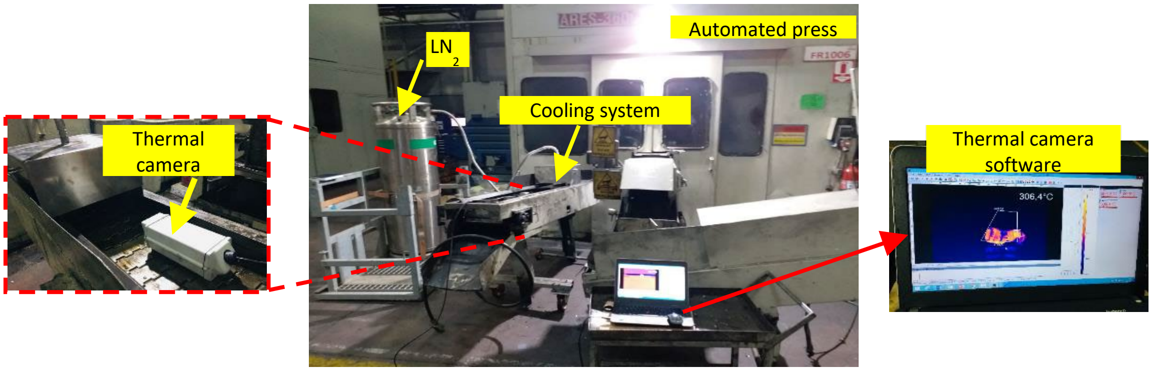

Fig. 2. Forging press and experimental setup.

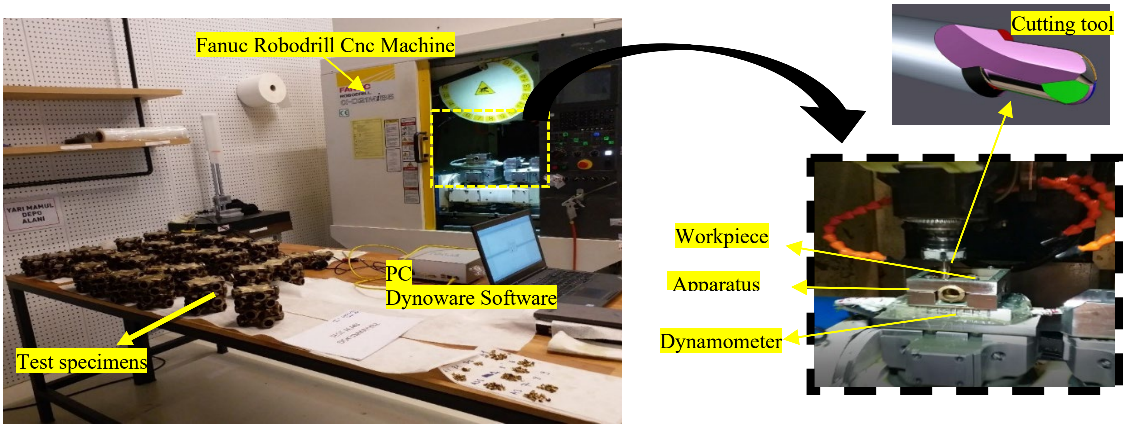

Fig. 3. The used experimental setup for the machining tests.

Table 2. The utilized parameters in hot forging and machining experiments.

Cu (%)	Forging Temperature (°C)	Cooling Duration (min.)	Rotational Speed (rpm)	Feed rate (mm/min.)
61,7	750	1 (LN_2)	3000	300
62,9	780			
63,4	810			

Results and Discussions

β Phase Analysis.

The β% phase ratio and its distribution are the most important factors affecting machinability. In this section, β phases are more clearly expressed by the red color in phase analysis microstructural distributions while the yellowish colors represent α phase. In the case of the material with the lowest Cu content of 61.7%, its intermetallic β% phase is higher compared to the other materials. In the Cu-Zn equilibrium diagram, the percentage of the β phase is controlled by the percentage of Zn, subsequently the Cu% content, and the thermomechanical process. The β phase percentage increased with Zn content, as expected, in the case where the zinc-rich and associated Cu% was the lowest. The β phase (Cu-Zn), an ordered type of intermetallic phase with a body-centered cubic crystal structure, (Cu) is a face-centered cubic crystal which expresses the solid solution, is structurally harder and less ductile than the α-phase. Zinc has the hexagonal close-packed (HCP) lattice structure [17]. The distribution and sizes of these phases have a significant effect on machinability [18]. The presence of the beta phase reduces the ductility of the alloy and thus the segmentation of the chips formed after machining. The morphology exhibited by the β phases and the increase in the percentage distribution in the structure cause a slight increase in hardness and low ductility, as a result, machinability, and chip breakability during machining increase with the increasing beta phase [8, 19]. The measured results from the microstructural analysis of β phase distributions in Fig. 4 demonstrate the effect of the %Cu and forging temperature on the distribution of β% phases in the material. The β phases in the structure showed a decreasing trend in terms of distribution and percentage with the increase of Cu%. This situation can be explained by the decreasing zinc distribution with the increase of Cu% in the structure. β phase is rich in zinc elements. Especially at high forging temperatures, the 61.7% Cu material rises to the point where the percent β phases are at their maximum during the process. By rapid cryogenic cooling, these β phases are being restrained in the brass material's internal structure [20]. In other words, the necessary time duration and temperature are not given for the β phases in the structure, such as slow cooling, to dissolve and turn into the α phase. In the case of forging at 750 °C forging temperature, approximately 70% less β phase distribution is obtained from the 61.7% Cu sample, whereas in 63.4% Cu specimen this value is around 63%. While there was no significant change in the β% phase ratios of the forging temperature in the 61.7% Cu sample, there was a decrease of approximately 22% from 750 °C to 810°C in the 62.9% Cu specimen, and an increase of approximately 25% was observed in the 63.4% Cu workpieces. There were no significant changes in the β phase distribution of the forging temperature in the samples with a low %Cu, but no clear distributions in the β% phase in the material with an increase in the Cu% could be obtained. It can be said that this is caused by the decrease in the percentage of zinc in the structure with the increase of %Cu.

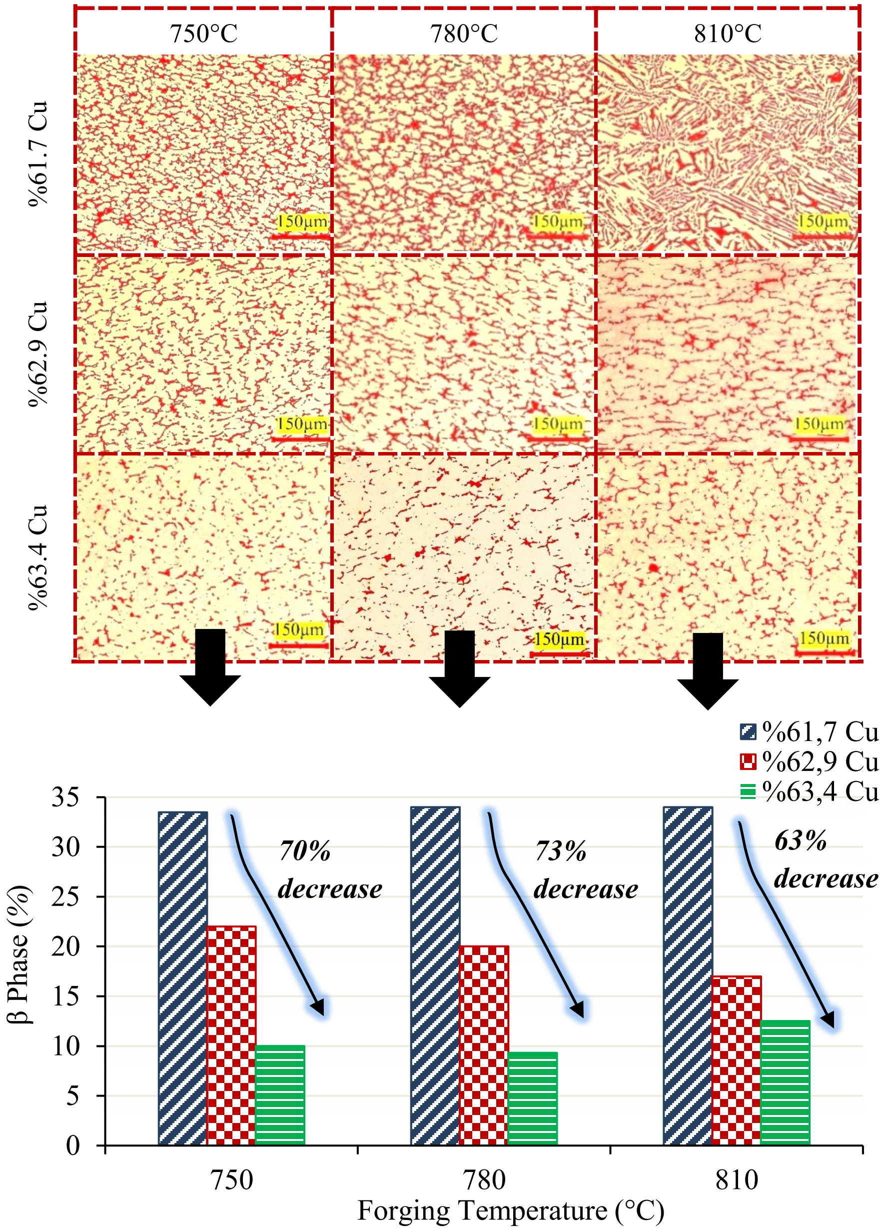

Fig. 4. Effect of Copper content and forging temperature on the beta phases of material.

Cutting Forces.

One of the copper alloys, CW511L, is a low lead alloy that is difficult to machine than other brass alloys [15]. This may therefore result in excessive cutting forces and other machining operations [2]. The feed force is the primary cutting force affecting the cutting tool. Under normal conditions, major variations in cutting forces and machinability qualities are primarily influenced by machining cutting parameters such as speed, feed, and cutting tool geometry. Alloy microstructure and mechanical characteristics affect an alloy's machinability. While the machinability of the metal depends on the metal's microstructural changes, the power consumption depends on the metal's mechanical characteristics [20]. In this instance, β phases and hence hardness is also impacted. The size of the interphase boundaries, which are influenced by the β-phase content and the size of the α-phase crystals, can be increased to enhance machining. In general, soft materials use less energy than hard metals, and tool wear is reduced. Finer grain sizes are advantageous for mechanical qualities, and since they are stronger and more ductile than coarser grains and possess higher machinability. Additionally, imperfections in the material's structure may have an impact on chip breakability and therefore machinability [18].

The average of three repetition cutting forces generated during drilling operation are presented in Fig. 5 according to the Cu% and the forging temperature. A close examination of the graph reveals a considerable impact of the Cu% ratio. It has been noted that the alterations made result in considerable variations in terms of machinability, especially given that these three Cu% ratios are CW511L despite being the same material. The dispersion of the β phases increased with the reduction of Cu%, and as a result, greater β phase distribution and finer α crystals tend to produce longer interphase boundaries, and microstructural distributions significantly influence on the machinability [18]. With an increase in the Cu%, it is seen that the cutting forces increase and the machinability decreases. An increase in cutting forces with significant friction in the contact area may occur in alloys with a ductile phase and low lead content in high FCC lattice structures [6]. This is confirmed by the fact that cutting forces rise with higher phases due to an increase in the Cu%. Once again, in different research [21], machinability tests on various copper alloys were conducted, and it was found that the alloys that we may refer to as zinc-poor or copper-rich yielded the greatest results in terms of cutting forces. At 750°C of forging temperature, 885 N force was attained at a rate of 61.7% copper, a rise of about 23% at a rate of 62.9% copper, an average of 1092 N, and an increase of roughly 36% at a rate of 63.4% copper, resulting in a force value of 1207 N. As can be observed, when the Cu ratio is lowest, the dominating β phases, and smaller grain sizes of the α phases facilitate cutting. In comparison to coarse grains, grains with a finer structure in terms of grain sizes enhance the structure and improve workability [20]. At 780°C forging temperature, 864 N force was measured in 61.7% Cu material, while an increase of roughly 27% at 62.9% Cu, an average of 1099 N, and 63.4% Cu, an increase of nearly 42%, and a force value of 1224 N was recorded. According to the obtained results, forging temperature has no impact on the cutting forces needed for machinability. 869 N force was obtained at 810°C forging temperature at a rate of 61.7% Cu, whereas 1183 N average force was obtained with an increase of almost 36% at a rate of 62.9% Cu, and this ratio was the highest percent increase compared to lower forging temperatures. There was a rise of about 43% and a force value of almost 1240 N was generated at the rate of 63.4% Cu.

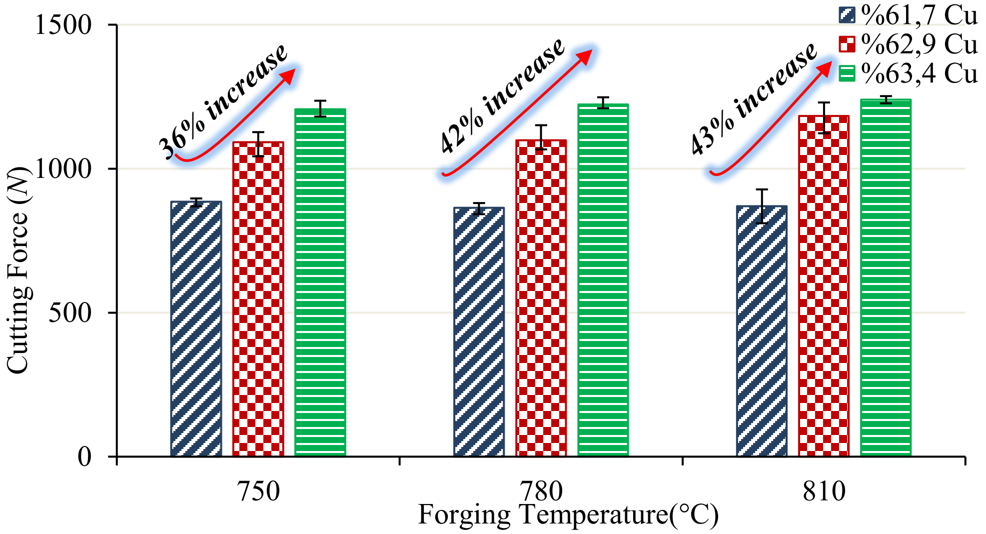

Fig. 5. The average measured cutting forces.

Surface Roughness.

The surface quality of the machined components is a desired characteristic and maintaining high surface quality is always one of the most crucial duties after machining. Surface roughness is known to impact a part's heat conductivity, friction, corrosion, and fatigue life [22]. In specific situations, machining factors such as feed and cutting tool tip radius have an impact on surface roughness [23]. However, since consistent speed, feed, and cutting tools were employed in this investigation, additional knowledge was gained about how the forging parameters and therefore the change in the material effect the machining and hence the change in the desired surface quality. Cutting tools that have been improperly ground have a propensity to scratch soft materials, like brass, leading to a poor surface finish. Fig. 6 shows the variations in surface roughness (Ra) values of the three different Cu% samples formed at 750-780 and 810°C forging temperatures as a result of changes in parameters following the cryogenic cooling process. The illustrated results represent the average of five measurements. When the graph is inspected, the roughness values decrease as Cu% increases. This means that improving the ductility of the outer surface with an increase in Cu% will result in a higher surface quality. While hard materials produce more clastic chips, it may be claimed that ductile materials provide superior surfaces with somewhat more continuous chip formation. Considering the roughness values at 750°C forging temperature, the highest roughness value was found in the material with a Cu content of 61.7%. The measured value in this condition is typically 0.52 µm. With an average roughness value of 0.43 µm measured at 62.9% Cu, it produces a value that is around 17% less than that of 61.7% Cu, while a 17–18% change was seen at 63.4% Cu ratio. At 780°C forging temperature, the highest roughness value was found in the material with a Cu content of 61.7%. In this condition, the measured value is around 0.49 µm on average. With an average roughness value of 0.37 µm measured at 62.9% Cu, a value was approximately 24% less than that of 61.7% Cu material, while a decrease of approximately 18% was observed in 63.4% Cu material. It can be interpreted that the rate of change in the roughness values of Cu% ratio decreases to minimum levels under the condition of the highest forging temperature in the experiments.

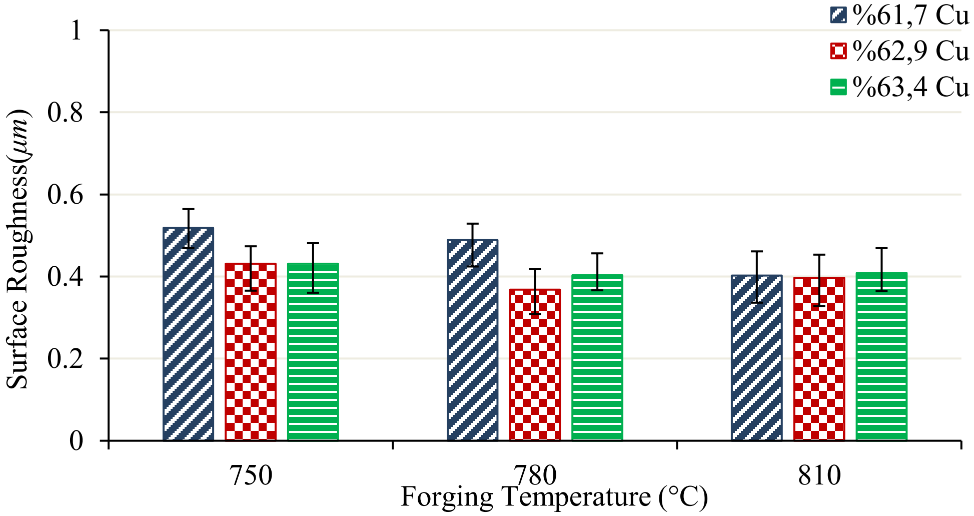

Fig. 6. The average values of the surface roughness (Ra) of the generated holes.

Dimensional Accuracy.

The dimensions and geometric tolerances in the component geometry are extremely important, much as the surface quality attributes of the machined item. After the manufacturing of parts, significant efforts are undertaken, particularly in industry, to obtain products with the appropriate dimensions and quality. Softer materials are more prone to bend when subjected to cutting tool pressure, decreasing dimensional accuracy. High-strength alloys may require carbide tools, grinding, and in certain conditions heat treatment for optimal manufacturing, whereas soft coppers and brasses may be machined rather readily [20]. The diametrical variations of the Ø12 holes that were produced after drilling in materials with various Cu contents of test specimens that were forged at different forging temperatures and treated to cryogenic cooling are shown in Fig. 7. Examining the graph reveals that the Cu% has some influence because, under all conditions, the hole sizes fall within the specified tolerance range. Additionally, it can be observed that holes in samples with a Cu ratio of 63.4% take values that are closer to the nominal size. The ductility of the material allows for a superior surface topography in the scenario when the Cu% ratio is at its highest, and the surface roughness values shown in the preceding section further corroborate this claim. However, experiments with the cutting tool in sequential conditions are required before it can be said that this is long-term. Because issues like lengthy chips, continuous chip status, and surface roughness that can result from chip removal from ductile materials can damage cutting tools and result in additional quality issues. It is typical for these graphical findings to show little fluctuations since the correct cutting tool dimensions are the most crucial aspect of dimensional variations. However, even if there is a change at low levels, the impact of this will be assessed as the impact of material and forging parameters will be explored within the scope of the research.

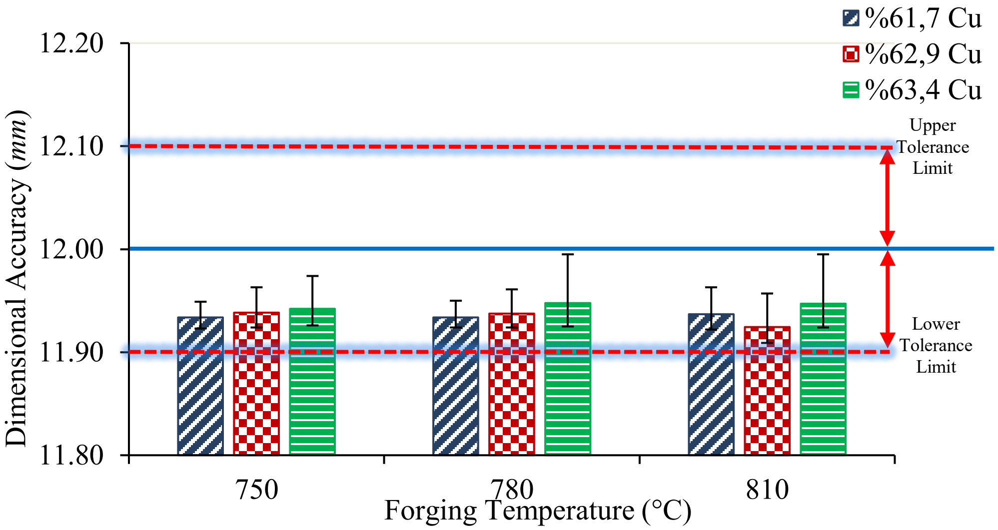

Fig. 7. The variation of the dimensional accuracy values of the generated holes.

Summary

In this research, the machining performance of CW511L material—one of the copper alloy-based lead-free brass materials—was explored by comparing its microstructural characteristics after forging. With the hot forging of the test sample at the correct temperature values, the β% phases in the structure increase to extremely high levels, and in this instance, the Cu% ratio has a major impact. This is a crucial step for machining because it ensures that most of these β phases remain in the structure without transformation (starting with the regular structure) by the action of cryogenic cooling. Additionally, the cutting forces clearly indicate the influence of the forging temperature, the Cu% ratio, and indirectly the distribution of β phases, as well as the influence of the input parameters on the outcomes for roughness and dimensional accuracy. The study is notable because, despite the fact that all of the samples used for the testing were CW511L, there was a substantial variation in the machinability of three distinct CW511L materials that were chosen from the standard range and in the machining tests.

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