CHARACTERIZATION OF THE PROPERTIES AND ACICULAR MICROSTRUCTURE OF A LEAD-FREE COPPER ALLOY

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Abstract

This paper concerns the characteristics of the material considered as one of the potentially applicable ones under the research topic "Sustainable lead-free fittings for drinking water and gas installations - machinability and connection possibilities".One of the main assumptions of the project were eliminating the recrystallization annealing process because of the use of controlled cooling after forging. The test material was lead-free brass CuZn21Si3P. The subject of the research is the thermoplastic forming process, which allows determining the relationship between the influence of the deformation amount, the temperature at the beginning and end of forging, and the cooling rate on the formation of an acicular structure. The tests were carried out on a mechanical press after heating the samples to temperatures of 700 °C, 770 °C and 820 °C. Strain values of 50% and 70% were used. After the process, the samples were cooled using a laboratory tunnel or in air. Then, the quality of the forging was classified based on surface observations. This work discusses the deformation conditions that cause the formation of a relief on the surface of the tested samples, which indicates the overheating of the material and the presence of an acicular structure in it.

Keywords: CuZn21Si3P, lead-free brass, thermoplastic forming process, acicular microstructure

1. INTRODUCTION

This work delves into the properties of a material deemed potentially applicable for the research topic “Sustainable lead-free fittings for drinking water and gas installations - machinability and connection possibilities”. This study is an extension of the research conducted as part of the project “Development and implementation of innovative connectors made of lead-free copper alloys for drinking, sanitary and technical water installations with reduced flow resistance for connections in installations based on PE pipes”. The project was motivated by several needs, including lower energy demand for circulation pumps, reduced material consumption in production, full safety of use, cost reduction, and reduction of CO_2 produced during the annealing process. To achieve these goals, the project assumed an increase in the internal diameter of the connector stub (from 7 to 9 mm), the use of lead-free copper alloys, and controlling the cooling of the connectors after forging instead of the annealing process.

The test material was lead-free brass CuZn21Si3P, the use of which is a response to restrictions on lead content. An example of such restrictions is the DWD Directive 2020/2184, according to which for all new materials in contact with drinking water, the lead content in tap water should not exceed 5 µg/L [1]. The CuZn21Si3P alloy can be an alternative to copper-lead alloys in terms of machinability [2] and resistance to dezincification [3, 4]. In addition, with a silicon content greater than 2 wt%, CW724R is resistant to stress corrosion cracking [5]. Resistance to stress corrosion cracking and dezincification is possible thanks to the noble phases present in the alloy and the presence of phosphorus, which acts as a corrosion inhibitor [6]. This alloy is suitable for the production of turned parts as well as for hot stamping. Phase changes at higher temperatures are crucial to this process, so deep knowledge of hot stamping is necessary. CW724R complies with ELV and RoHS regulations and meets EU drinking water requirements [7]. All these properties make CW724R a high-performance material that is used in many areas such as electronics, automotive and sanitary facilities [8].

The research presented here focuses on the thermoplastic forming process, which allows for determining the relationship between the amount of deformation, the temperature at the beginning and end of forging, and the cooling rate on the formation of the acicular structure in samples with different nominal dimensions. The tests were carried out on a stand equipped with a mechanical press and a laboratory cooling tunnel, which allowed for the control of the cooling speed using a knob. Tests were performed for the following parameters: temperature: 700°C, 770°C, 820°C; deformation degree: 50%, 70%. After the process, the samples were cooled with or without a cooling tunnel (max. and min. power).

2. MATERIALS AND METHODOLOGY

The test material was lead-free brass with silicon – CuZn21Si3P. These were extruded and annealed bars with a diameter of 20, 25 and 30 mm as delivered. The material was cut into samples 35 mm high. The chemical composition of the tested alloys is presented in **Table 1**.

Table 1 Chemical composition of the tested material [9]

Element	Cu	Al	Fe	Mn	Ni	P	Pb	Si	Sn	Zn	Others total
min	75.0	-	-	-	-	0.02	-	2.7	-	Rem.	-
max	77.0	0.05	0.3	0.05	0.2	0.10	0.1	3.5	0.3	-	0.2

The microstructure of the material was revealed using a 10% aqueous solution of ammonium persulfate and was examined using an OLYMPUS BX53M light microscope and is shown in cross-section in **Figure 1**. This alloy is characterized by a heterogeneous structure composed of the α matrix and κ and γ silicon phases. The hardness as delivered was measured using the Vickers method at a load of 1 kgf, which was 140 HV1.

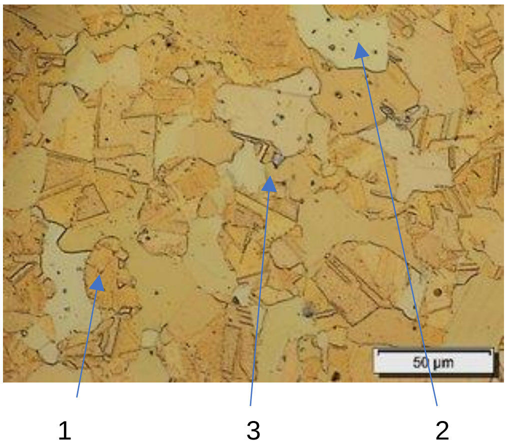


Figure 1 Microstructure of alloy with marked microstructural components, where: 1 – alpha-phase, 2 – kappa-phase, 3 – gamma-phase

The tests were carried out on a stand equipped with a mechanical press (**Figure 2a**) and a laboratory cooling tunnel (**Figure 2b**) allowing the knob to control the cooling speed. Tests were carried out for the following parameters: temperatures: 700 °C, 770 °C, 820 °C, deformation degree: 50%, 70%. After the deformation process, the samples were cooled using a cooling tunnel (max and min power) or bypassing the tunnel. Samples after thermomechanical processing are shown in **Figure 3**.

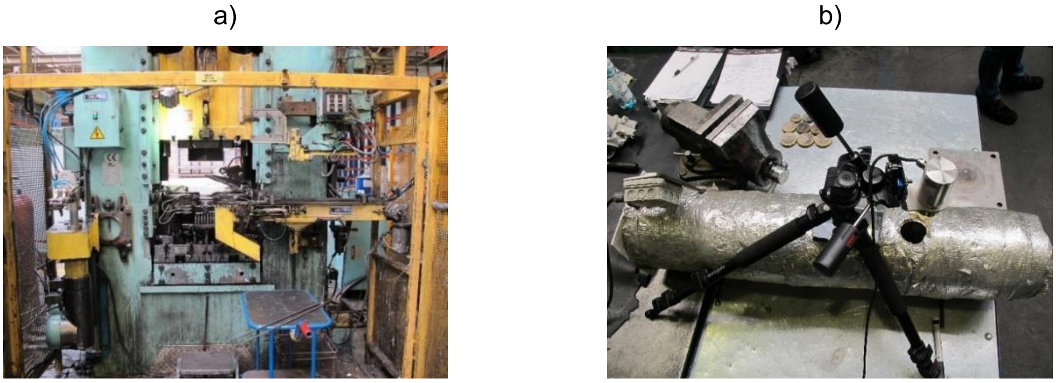


Figure 2 a) mechanical press, b) cooling tunnel

Figure 3 Samples after thermo-mechanical treatment

Then, the thermoplastic treatment was assessed on the surface quality. The results are visible in **Figure 4**.

the highest acceptable surface quality, without banding and furrowing

acceptable surface quality without cracks but with visible furrowing

the relief formed on the surface indicates the limit of acceptability of deformation conditions

unacceptable deformation conditions due to the relief forming on the surface indicating overheating of the material and the formation of a coniferous structure

unacceptable surface quality with visible microcracks

definitely unacceptable surface quality due to the presence of deep cracks extending to the contact surface with the tool

Figure 4 The influence of thermoplastic treatment on surface quality

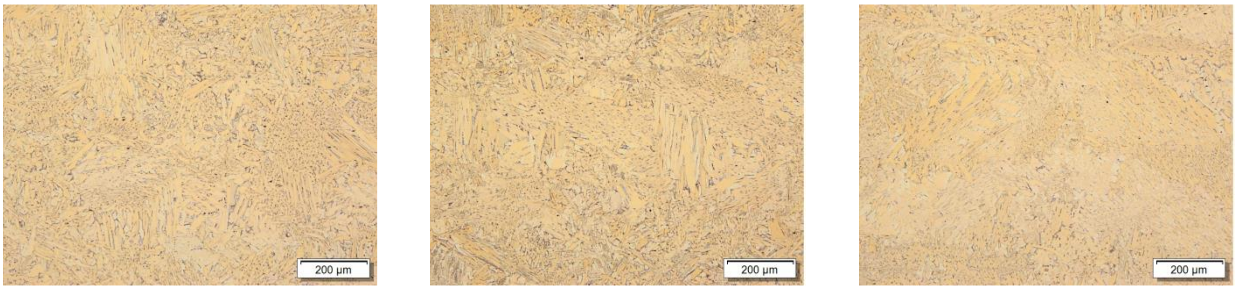
3. RESEARCH RESULTS AND DISCUSSION

After the thermoplastic treatment process, the quality of the forging was classified based on surface observations. This work discusses unacceptable deformation conditions causing the formation of a relief on the surface of the tested samples, which indicates overheating of the material and the presence of an acicular structure in it. The results with unacceptable surface quality are listed in **Table 2**.

Table 2 Some of process parameters for unacceptable surface quality

Sample No.	**Start diameter** (mm)	**Start temperature** (°C)	**Compression rate** (%)	**Quenching**
44a	30	770	50	Max
43a	30	770	50	Min
45a	30	770	50	Air
11a	20	770	70	Max
29a	25	770	70	Max
47a	30	770	70	Max
17a	20	820	70	Max
53a	30	820	70	Max
10a	20	770	70	Min
28a	25	770	70	Min
46a	30	770	70	Min
30a	25	770	70	Air
48a	30	770	70	Air
36a	25	820	70	Air

Then, the microstructure and hardness of the samples were assessed. Hardnesses performed using the Vickers method at a load of 30 kgf. **Figure 5** summarizes the results for a deformation degree of 50% at a temperature of 770 °C and various cooling rates. In each case, an acicular structure with an increased content of the gamma phase was obtained.



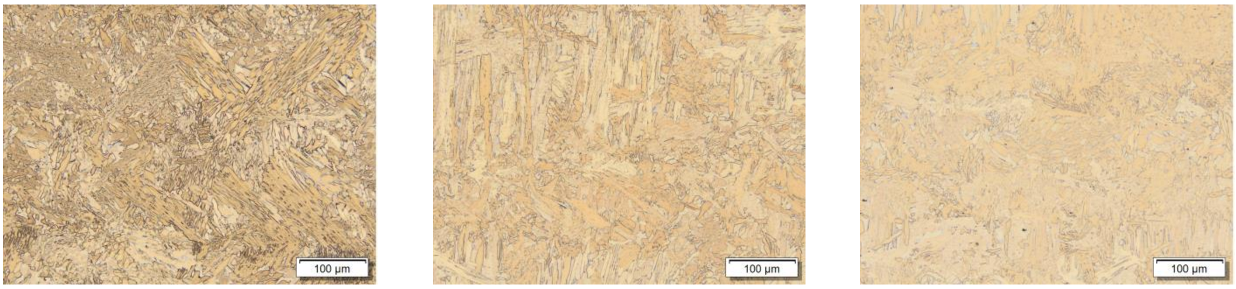
44a 30 mm/770°C/50%/max
142 HV30

43a 30 mm/770°C/50%/min
136 HV30

45a 30 mm/770°C/50%/air
141 HV30

Figure 5 Compression rate 50%

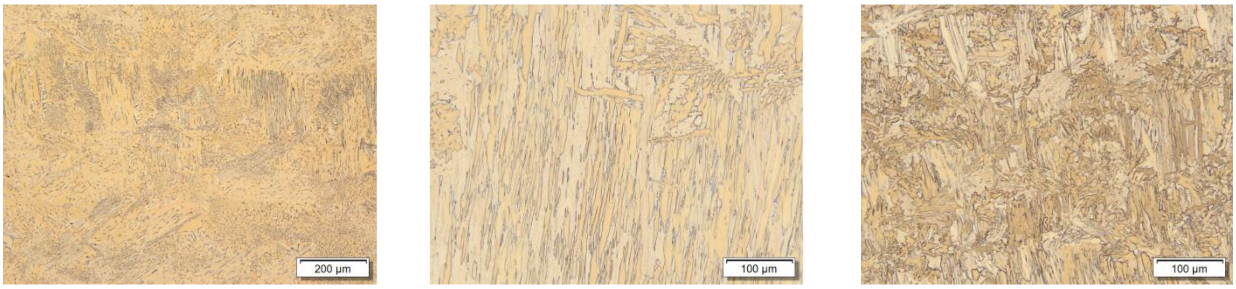
Figure 6 summarizes the results for a deformation degree of 70% at a temperature of 770 °C and 820 °C and various cooling rates. In each case, an acicular structure with an increased content of the gamma phase was obtained.



11a 20 mm/770°C/70%/max **152 HV30**

29a 25 mm/770°C/70%/max **151 HV30**

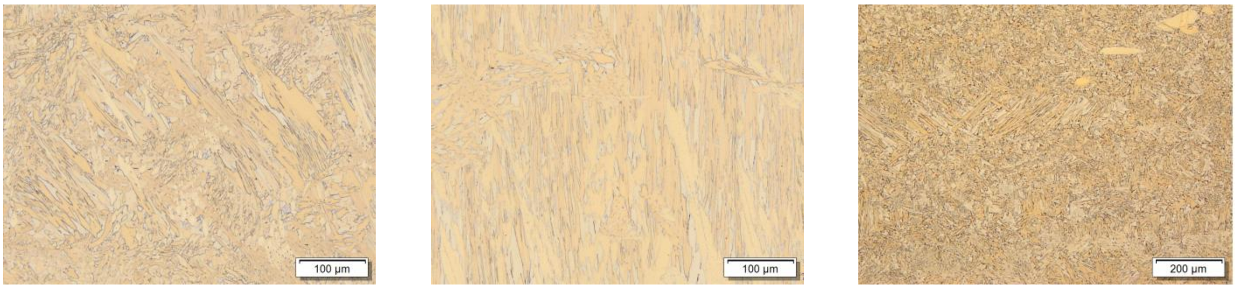
47a 30 mm/770°C/70%/max **153 HV30**



17a 20 mm/820°C/70%/max **148 HV30**

53a 30 mm/820°C/70%/min **152 HV30**

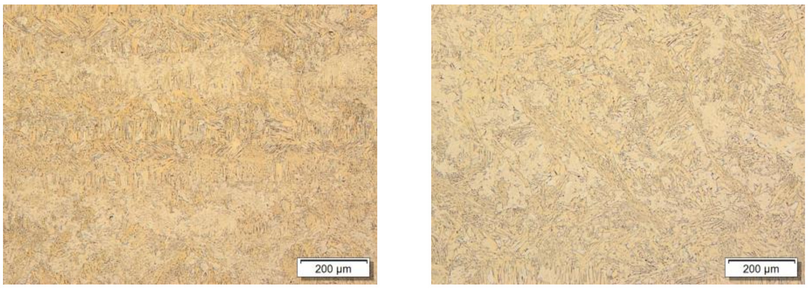
10a 20 mm/770°C/70%/min **154 HV30**



28a 25 mm/770°C/70%/min **154 HV30**

46a 30 mm/770°C/70%/min **152 HV30**

30a 25 mm/770°C/70%/air **154 HV30**



48a 30 mm/770°C/70%/air **157 HV30**

36a 25 mm/820°C/70%/air **145 HV30**

Figure 6 Compression rate 70%

4. SUMMARY AND CONCLUSIONS

The thermoplastic shaping process is crucial to obtaining optimal material properties. Properties such as hardness, tensile strength and abrasion resistance are directly related to the microstructure of the material, which is shaped by this process. The research shows that the acicular structure that characterizes samples from the black and black-celadon categories occurs in samples heated to a temperature of 770 °C and higher. At temperatures above 770 °C, the formation of an acicular structure is independent of the cooling rate. This discovery is important because the acicular structure influences the mechanical properties of the material, such as hardness and strength. The degree of deformation also affects the material properties. Studies have shown that a deformation degree of 50% does not significantly affect the strengthening of the material, while an increase in hardness can be observed at a deformation of 70%. This shows that understanding the impact of deformation on material properties is crucial for optimizing the thermoplastic forming process. Additionally, the tests showed that the nominal sample size does not affect the occurrence of an acicular structure with the thermoplastic processing parameters used. This suggests that the thermoplastic forming process can be scaled effectively without losing control over the material structure. In summary, understanding the thermoplastic forming process is crucial to obtaining optimal material properties. This allows for precise control of the material's microstructure, which in turn affects its mechanical properties. That is why it is so important to conduct further research in this field.

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