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Research Article

Study on the Microstructure of Hot Deformed Cu-28Zn Prealloyed Powder Compacts

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ABSTRACT

The role of microstructure on hot deformation behavior of sintered Cu-28Zn prealloyed powder compacts was investigated by a series of isothermal hot compression tests in the temperature range of 550- 850°C at strain rates of 0.001, 0.01, 0.1 and 0.5 s^{-1}, by taking into consideration the Hyperbolic Sine functional behavior to analyze the deformation behavior of the alloy. The results indicate that dynamic recrystallization (DRX) has occurred in a large scale. The DRX nucleation sites are along initial grain boundaries, inside the twin bands and triple junctions. In all stress- strain curves in strains more than 0.2 dynamic recovery (DRV) and DRX take place simultaneously. The effect of strain rate and temperature on dynamically recrystallized grain refinement was investigated. Microstructure is in compliance with the results through the Zener-Hollomon relation and has satisfied hot deformation stress- strain curves. This study may provide a new understanding on hot plastic deformation of sintered prealloyed particles microstructure. The results obtained can be used to develop and optimize the conditions of hot plastic deformation of similar prealloyed powder compact.

1. Introduction

Hot forging is considered as one of the most significant processes to produce components which have appropriate mechanical properties as well as suitable metallurgical structures [1]. Understanding the hot flow stress is highly crucial in metal forming processes like rolling and forging [2, 3]. Microstructural evolution and deformation mechanisms in the deformation process are intimately concerned with flow stress [4]. The material flow behavior is affected by numerous parameters, for instance strain, strain rate, temperature and so on. It is a hard task to understand their impacts in view of their complicated nature [1]. Hence, a remarkable amount of investigation has been conducted to model the flow stress of metals and alloys in accordance with the empirical findings so as to apply more advanced modeling methods, including finite element analysis [5], as well as numerical simulations [1]. Through hot deformation, the strain hardening and restoration processes, as well as the dynamic recovery and dynamic recrystallization tend to be observed [6], which should be met by the flow stress model. Several researchers have made efforts to formulate the materials constitutive equations and proposed their own formulations through placing the empirically measured data into one single equation [7]. Dynamic recrystallization (DRX) is a crucial phenomenon to keep the microstructural and mechanical features regarding hot working in control.

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Barnett, has shown that the dynamic recrystallization grain size is less sensitive to deformation conditions than that of other metals [8]. When examining the effect of strain rate and temperature, it is often useful to combine both terms into the Zener-Hollomon parameter. With respect to the macroscopic data obtained from mechanical experiments in comparison with the microscopic data derived from metallurgical researches, in the light of its less time-consuming and less costly nature, the mathematical and macroscopic dimensions of the dynamic recrystallization process are taken into account in this model.

Alpha brass alloys are widely used as an industrial material because of their excellent characteristics such as high corrosion resistance, diamagnetism, good deformability and machinability [9]. Basic applications in automotive industries for brass powder metallurgy (PM) parts include bearings and synchronizer rings. Generally sintered brass parts are commonly made from prealloyed atomized powders [10]. High temperature mechanical properties and the constitutive equation of the specimen in the sintering temperature are needed to stimulate the behavior of Cu-28Zn in different situations and are achieved by conducting hot compression test. This analysis has been conducted for the hot compression flow curve of pressed and sintered Cu-28Zn, which is a useful model material, that can be easily processed by powder metallurgy and exhibiting a fairly uniform, single phase microstructure. The aim of this research is to clarify the microstructural changes that take place throughout a hot compression test under various temperature and strain rates.

2. Materials and Experimental Procedure

For hot compression experiments, cylindrical samples with 14.5 mm height and 10 mm diameter were produced from water atomized prealloyed brass powder, Cu-28Zn. The brass powder was blended with 0.75wt% lithium stearate as a lubricant and compacted at a pressure of 600 MPa. Afterwards the green compacts, with green density of 7.47 g cm^{-3}, were sintered at the optimum temperature of 860˚C for 20 minutes in N_2 atmosphere of technical quality, the process being precisely based upon the fabrication parameters mentioned in [11, 12]. The predefined porosity and sintered density were 9.4% and 7.61 g cm^{-3}, respectively. A scanning electron micrograph of the Cu-28Zn powder is shown in Fig. 1, and the properties of the brass powder are listed in Table 1.

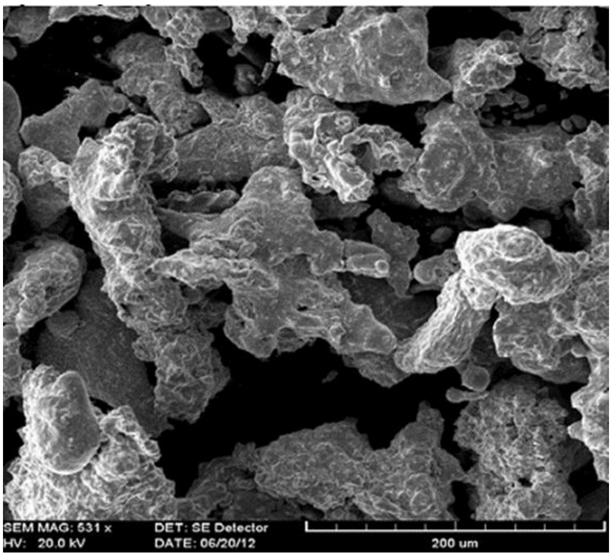


Fig. 1. Scanning electron micrograph of the as-received brass powder.

Table 1. Characteristics of Cu-28Zn prealloyed powder

Chemical analysis	
Cu	Balanced
Zn	28.6
Al	0.14
Fe	0.085
S	0.062
Si	0.054
P	0.0084
Physical properties	
Flowability (sec/50g)	21
Apparent density (g/cm^3)	3.2
Powder shape	Irregular
Sieve analysis	
Particle fraction (µm)	Weight percentage
125-180	9.75
90-125	24.63
63-90	23.53
<63	42.09

The hot compression experiments were performed on a GOTECH Al7000 universal testing machine coupled with a programmable resistance furnace and an instrument geometry which facilitates the fast quenching of the samples. A very thin Mica plate was employed for the minimization of the friction impact. The employed load was measured via a highly precise load cell (Model: SSMDJM- 20kN), that was capable of measuring the load forces down to 0.1 kgf. The displacement data were utilized to calculate the genuine strain values. The tests were carried out in the temperature range of 550-850˚C at a strain rate of 0.001, 0.01, 0.1 and 0.5 s^{-1}. Prior to conducting the hot compression tests, the samples were soaked at deformation temperature for a period of 5 min, and at the end of compression experiments the height decrease was 60%. After deformation, the samples were immediately quenched in water to maintain the deformed microstructure. The microstructure investigation was performed through optical microscopy (model: Olympus PMG3).

3. Results and Discussion

Isothermal hot compression flow stress curves at deformation temperatures of 550, 650, 750 and 850°C under different strain rates of 0.001, 0.01, 0.1 and 0.5 s^{-1} as depicted in Fig. 2.

As shown in Fig. 2 the true stress- true strain curve increases significantly towards higher stress with higher strain rate and lower temperature. This correlation in fact indicates the sensitivity of the flow stress to the variation of temperature and deformation strain rate. Additionally, deformation mechanisms and microstructure evolution during deformation have been reflected by the shape of the flow curve. The flow stress-strain behavior can be assorted into three categories. In the first one, work hardening and flow stress increase up to a critical point due to continuous confining of newly created mobile dislocations by older dislocations and microstructural obstructions (e. g. grain boundary and twin), followed by the second one which exhibits work hardening and dynamic recovery (DRV). Recovery involves partial restoration because the dislocations are not completely removed, but would lead to the formation of a metastable state. In the third one, DRV and dynamic recrystallization (DRX) take place simultaneously as indicated by the leveling out of the graph as well as the small difference between peak and steady state stress. During dynamic recrystallization, formation of new grains that are free of any dislocation occurs within the deformed structure. DRX nuclei grow and consume the existing grains, and the consequence is a new grain structure with low dislocation density. The effect of thermomechanical parameters on the flow stress-strain curve could be satisfactorily conveyed through microstructural exploration. In order to attain a simple approximation of the flow stress- strain curve, utilizing an Arrhenius-type equation can be used over a wide range of deformation conditions.

According to [12], constitutive equation can be rewritten as a function of deformation parameters as follows, Equations 1 and 2 and Table 2;

$$\dot{\varepsilon} = A[\sinh(\alpha\sigma)]^{n}\exp(-\frac{Q}{RT}) \quad (1)$$

$$\sigma = \frac{1}{\alpha}[\sinh^{-1}\left(\frac{Z}{A}\right)^{\frac{1}{n}}] \quad (2)$$

$$Z = \dot{\varepsilon}\exp(\frac{Q}{RT}) \quad (3)$$

Where $\alpha = \sum_{i=0}^{5}\alpha_i\varepsilon^i$, $n = \sum_{i=0}^{5}n_i\varepsilon^i$, $Q = \sum_{i=0}^{5}Q_i\varepsilon^i$, $\mathrm{LnA} = \sum_{i=0}^{5}A_i\varepsilon^i$;

The Zener–Hollomon parameter (Z) is commonly used to present the relationship between deformation variables, i.e. strain rate and temperature, and deformation of materials at elevated temperatures. As shown in Figures 3 and 4, the Z parameter is lowered by increasing temperature and decreasing strain rate.

Table 2. The polynomial fitting results of Q, ln A, α and n of sintered Cu–28Zn from pre-alloyed powder

α (MPa^{-1})	Q ($kJmol^{-1}$)	n	lnA(s^{-1})
α_0 =0.6703	Q_0=334.71	n_0=4.3992	A_0=30.222
α_1=-1.0225	Q_1=-979.79	n_1=19.468	A_1=67.556
α_2=7.4367	Q_2=5910.1	n_2=-250.43	A_2=-803.65
α_3=-24.388	Q_3=-16196	n_3=1014	A_3=3335.1
α_4=36.78	Q_4=21200	n_4=-1699.2	A_4=-5708.9
α_5=-20.752	Q_5=-10750	n_5=1020.5	A_5=3471.5

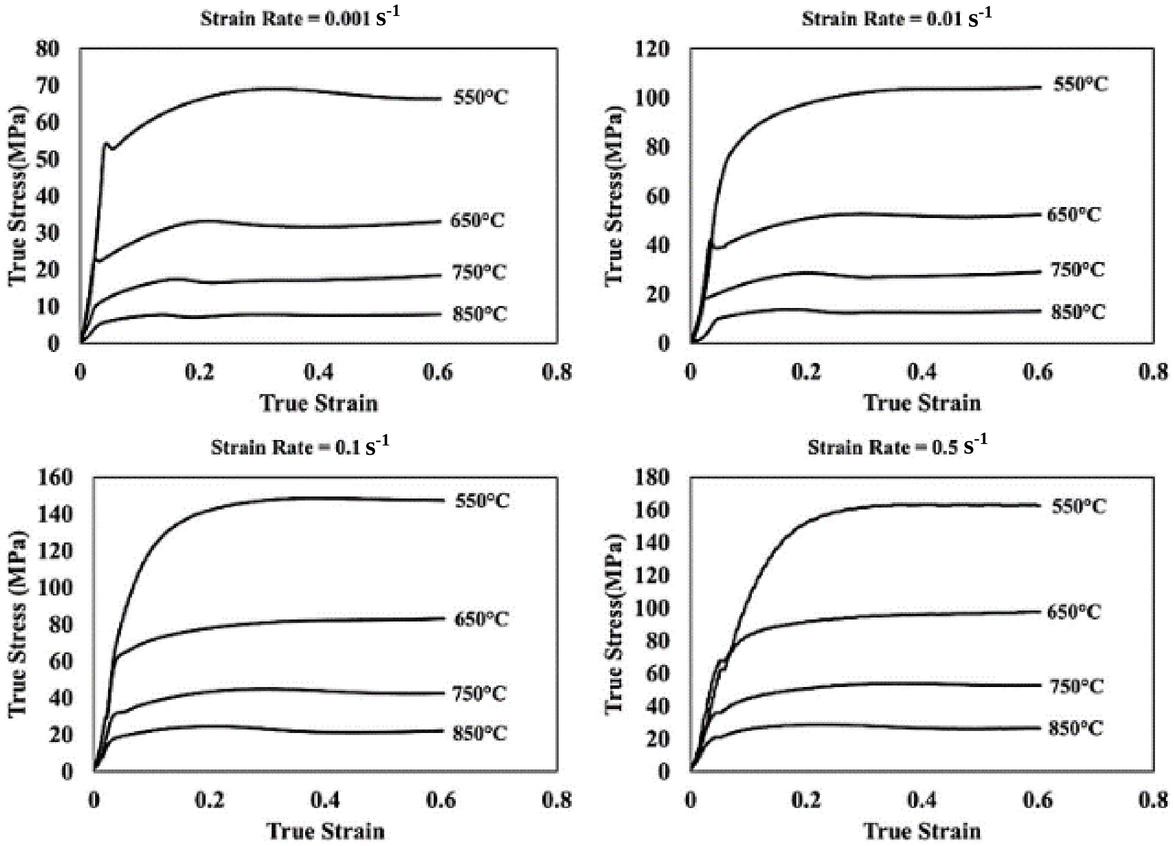


Fig. 2. True stress–true strain curves of sintered Cu-28Zn from pre-alloyed powder after hot compression tests at 550-850°C and at strain rates of 0.001, 0.01, 0.1 and 0.5 s^{-1}.

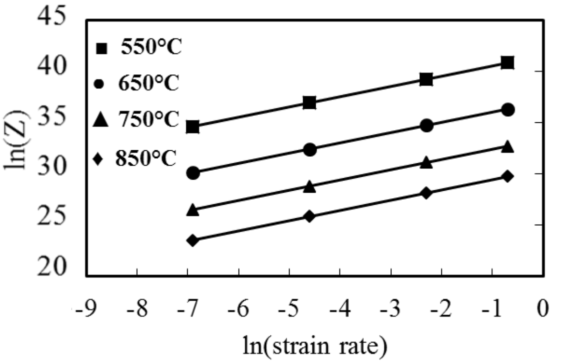


Fig. 3. The variation of Zener Hollomon parameter versus strain rate.

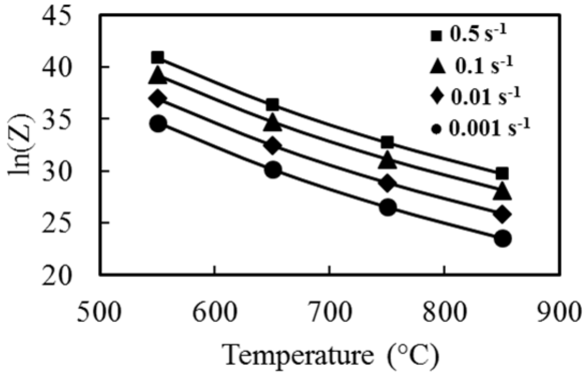


Fig. 4. The variation of Zener Hollomon parameter versus temperature.

In order to investigate the effect of hot deformation parameters on the microstructural evolution, the microstructures of the compressed specimens under the strain rate of 0.001, 0.01, 0.1 and 0.5 s^{-1} at a strain of 0.6 and different temperatures are shown in Figures 5 and 6. The optical microscopy observations show the dynamic recrystallization of brass.

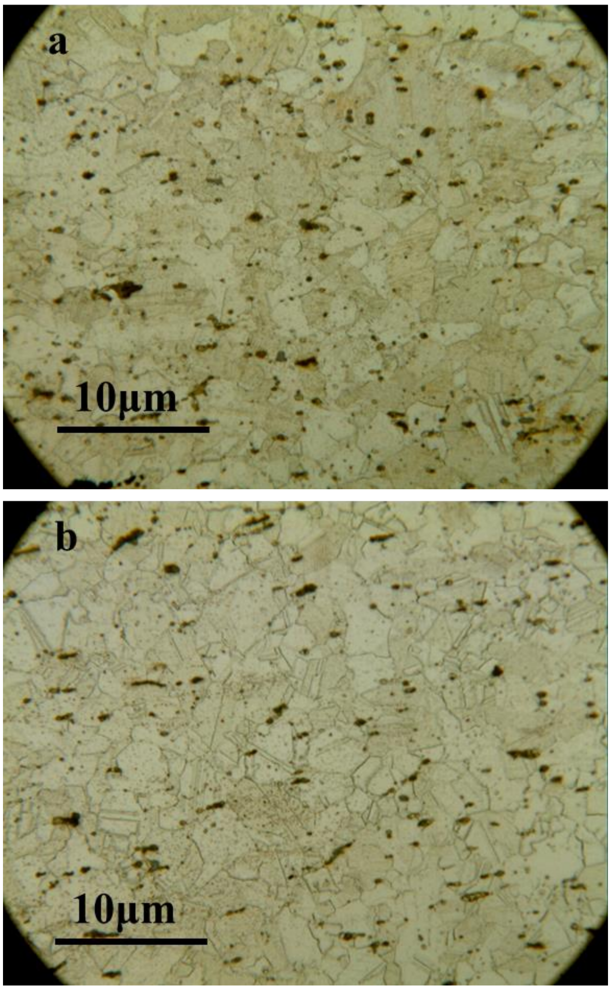
The recrystallized grains are much smaller and approximately equiaxed. They have been nucleated and grown along initial grain boundaries and inside the twin bands and triple junctions. Once the grain boundaries have been consumed by these 'new' grains, the recrystallization process will continue via nucleation at the interface between the recrystallized and non-recrystallized material. With the increase of deformation temperature a typical "necklace" microstructure comes into formation [13].

Figure 5 shows the variation of microstructure at a constant temperature of 650°C and strain rates of 0.001 s^{-1} (Fig. 5(a)), 0.01 s^{-1} (Fig. 5(b)), 0.1 s^{-1} (Fig. 5(c)), 0.5 s^{-1} (Fig. 5(d)).

Deformation at the lower strain rates will provide more time for the deformation heating to dissipate to the surroundings, while at the highest strain rate it is possible that there is insufficient time for any heat dissipation, and the deformation heating will be adiabatic. At these highest strain rates the grain boundaries could become saturated with newly formed DRX nuclei. It is, therefore, possible that these new grains have been formed by some kind of grain rotation caused by the subgrains in the vicinity of the grain boundaries obtaining a sufficiently high misorientation to form high angle boundaries [14-16].

Figure 6 shows the variation of microstructure at constant strain rate of 0.1 s^{-1} and temperature of 550°C (Fig. 6(a)), 650°C (Fig. 6(b)), 750°C (Fig. 6(c)), 850°C (Fig. 6(d)).

As was expected the DRX grain size increased with higher temperature. The higher the deformation temperature, the higher the degree of dynamic recrystallization.



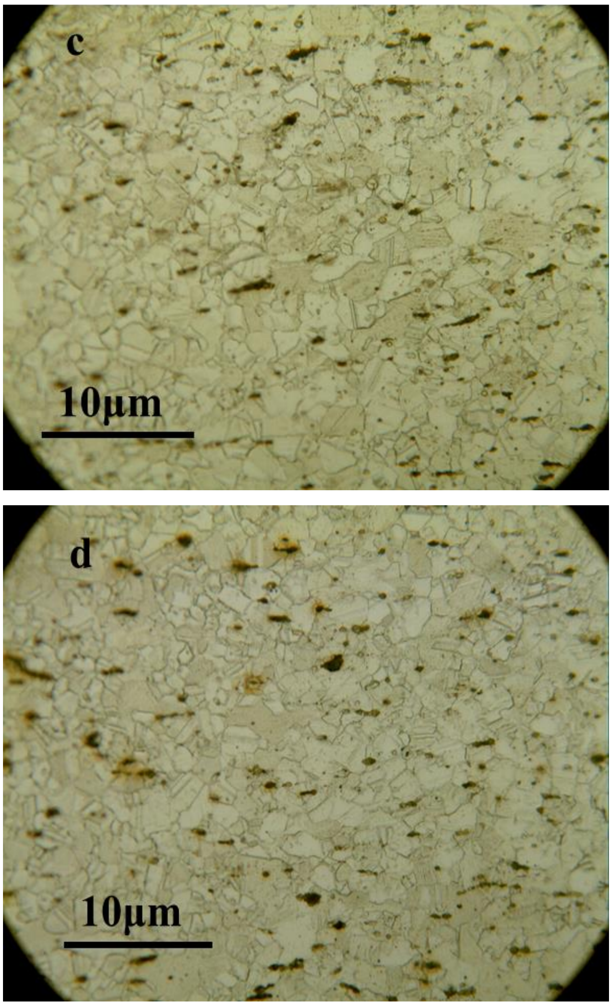


Fig. 5. Quenched microstructure after hot deformation at 650°C and strain rates of (a) 0.001s^{-1}, (b) 0.01s^{-1}, (c) 0.1 s^{-1}, (d) 0.5 s^{-1}.

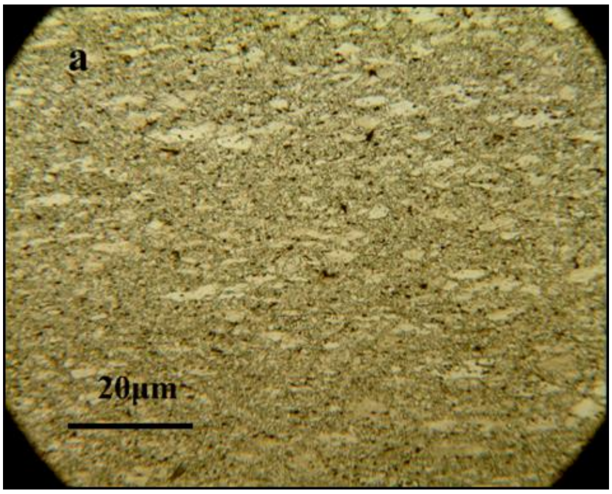


Fig. 6. Quenched microstructure after hot deformation at a strain rate of 0.1 s^{-1} and temperature of (a) 550°C, (b) 650°C, (c) 750°C, (d) 850°C.

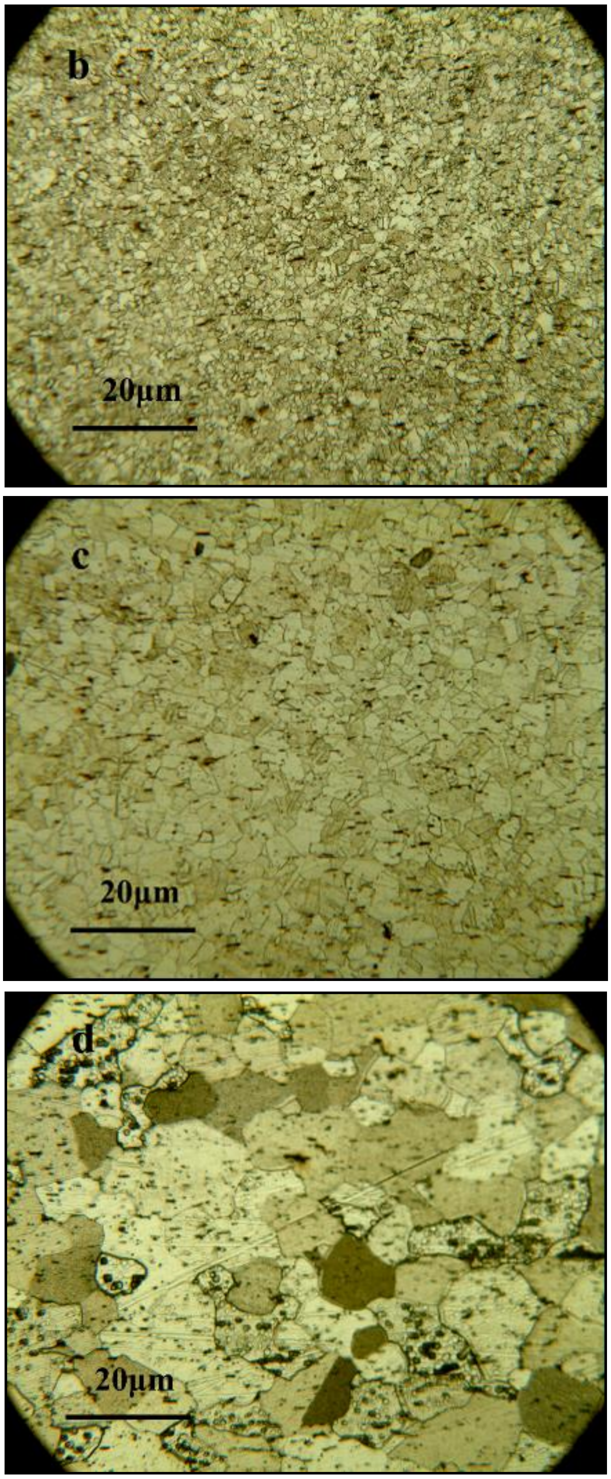


Fig. 6. Continue.

Apparently, due to the relatively high diffusion rate (the lattice and grain boundary diffusion rates) in copper alloys [17], the diffusion controlled grain boundary sliding may greatly contribute to a total deformation at elevated temperatures and lower strain rates. The grain size of the hot deformed brass also depends on the Zener–Hollomon parameter (Z), i.e., decreasing of Z leads to more adequate proceeding of dynamic recrystallization [18]. The higher temperatures enhanced the annihilation rate and the lower strain rates decreased the rate of dislocation generation.

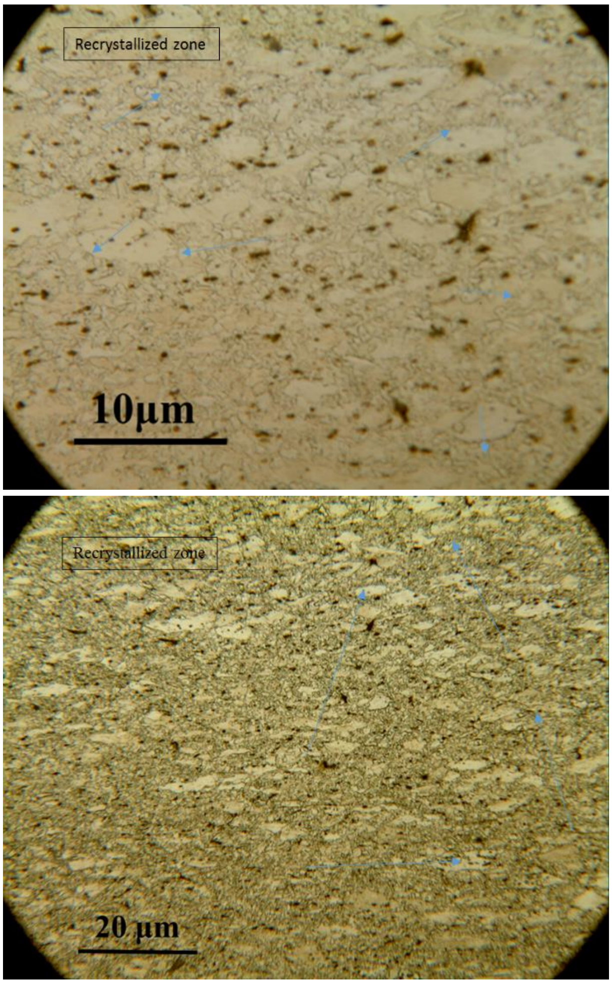


Fig. 7. Microstructure of brass hot deformed at T=550°C and strain rate=$0.1s^{-1}$.

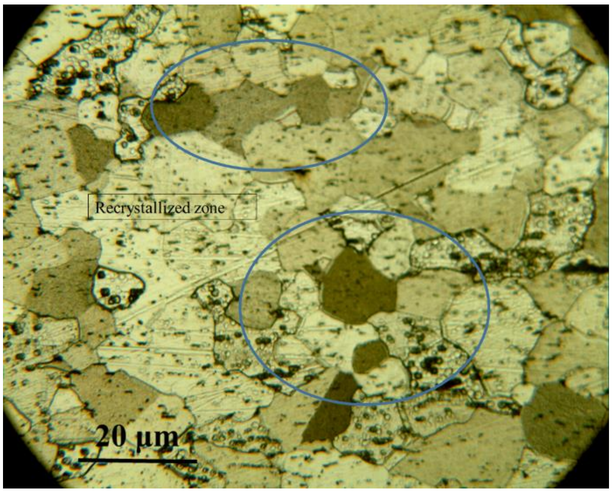


Fig. 8. Microstructure of brass hot deformed at T=850°C and strain rate=$0.1s^{-1}$.

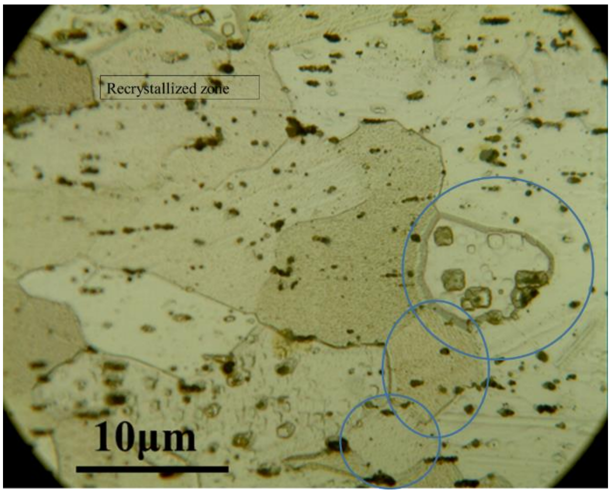


Fig. 8. Continue.

The phenomenon of partial recrystallization can be specified as shown by arrows in Fig. 7. Since the dislocation tangles are much denser within the twins and near the grain boundaries, these are the preferred sites for DRX grain formation at lower temperatures. On the other hand, the recrystallized regions of the compressed specimens at higher temperatures represent a distinct profile where the new grains develop considerably from boundaries to the center of the grain (Fig. 8).

4. Conclusions

In this work, the dynamic recrystallization behavior of powder metallurgy prealloyed Cu-28Zn has been investigated within a temperature range of 550-850 °C and at a strain rate of 0.001, 0.01, 0.1, 0.5 s^{-1} through isothermal deformation. The dynamic recrystallization is assumed as the major softening mechanism of sintered prealloyed Cu-28Zn during hot compression. The size and volume fraction of DRX grains increase with higher deformation temperature. The stress-strain curves exhibit two distinct types of restoration behavior, one with a peak stress followed by a gradual decline to a steady state stress (DRX), and the other a gradual stress increase to a peak followed by a steady state stress (DRV). Also, the absence of a peak stress did not always represent the absence of DRX. This finding was obtained from the quenched microstructure which illustrated original grain boundaries decorated with newly formed grains.

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مطالعه ریزساختار پودر پیش آلیاژی Cu-28Zn در طی فرایند تغییرشکل گرم

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چکیده

آزمون فشار گرم در نمونه‌های حاصل از تف‌جوشی پودر پیش‌آلیاژی Cu-28Zn در محدوده دمایی ۵۵۰-۸۵۰ درجه سانتیگراد و در نرخ‌کرنش‌های ۰/۰۰۱، ۰/۰۱، ۰/۱ و ۰/۵ (s^{-1}) برای بررسی ریزساختار در تغییر شکل گرم انجام گرفته است. تغییر شکل گرم در آلیاژ مذکور از تابع سینوس هایپربولیک تبعیت می‌کنند. نتایج نشان می‌دهد که تبلورمجدد دینامیکی به طور گسترده‌ای صورت گرفته است و درون باندهای دوقلویی، در راستای مرزدانه‌ها و اتصالات سه‌گانه از مکان‌های اصلی جوانه‌زنی تبلورمجدد دینامیکی می‌باشد. در کرنش‌های بزرگ‌تر از ۰/۲ بازیابی دینامیکی و تبلورمجدد دینامیکی همزمان انجام می‌گیرد. تأثیر نرخ کرنش و دما بر ریز شدن دانه‌های تبلورمجدد یافته بررسی شده و ریزساختار با نتایج حاصل از روابط زنر- هولمان و منحنی‌های تنش- کرنش تغییر شکل گرم مطابقت دارد. این مطالعه بررسی جدیدی بر روی ریزساختار حاصل از تغییر شکل گرم نمونه‌های پیش‌آلیاژی تف‌جوشی شده انجام می‌دهد. از نتایج بدست آمده می‌توان در توسعه و بهینه‌سازی شرایط تغییر شکل گرم برای نمونه‌های پودری پیش‌آلیاژی مشابه استفاده کرد.

واژه‌های کلیدی: بررسی ریزساختار، متالورژی پودر، آزمون فشار گرم، تبلورمجدد دینامیکی، آلیاژ برنج تف‌جوشی شده