논 문

Quantitative Evaluation of Machinability of Free-Cutting Phosphor Bronze Alloy by using a Piezoelectric Tool Dynamometer

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Abstract

절삭특성은 재료를 원하는 형상으로 가공하기 위해 재료의 불필요한 부분을 제거할 경우 그 가공성이 쉽거나 어려움에 대한 정도로 정의될 수 있는데 동합금 소재의 절삭특성은 절삭시 발생된 칩의 형상이나 길이를 측정하거나 또는 공구계에 부착된 토오크 미터에 의해 절삭력을 간접적으로 측정하는 방법등이 사용되어 오고 있다. 상기의 평가방법은 절삭특성의 간접적인 평가방법이라는 한계와 정확도에 문제가 있는 실정이다. 본 연구에서는 압전형 공구동력계(Piezoelectric Tool Dynamometer)를 쾌삭인청동합금 피절삭물에 직접 부착하여 절삭가공시 절삭력은 정량적으로 직접 측정하고자 하였다. 쾌삭인청동합금의 소둔 열처리 시간이 증가할수록 결정립의 성장에 의한 연화현상과 납입자의 군집화 (Clustering) 는 관찰되었으나 그로 인한 절삭력 및 절삭에 필요한 에너지의 변화는 뚜렷하지 않았다.

Key words : Free-cutting Phosphor Bronze Alloy, Quantitative Cutting Force Measurement, Piezoelectric Tool Dynamometer

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1. Introduction

The term 'Machinability' should ideally be characterized as an easily-machined and measured property and/or quality of material, to be used, inter alia, as an indicator of the difficulties to be experienced during machining; problems arise because a material may have good 'machinability in terms of cutting force' when assessed in terms of one criterion, but poor by another. Recognizing that the cutting force of materials is also dependant on the experimental set-up and the process details, it is clear that cutting force is not a simple property of the material, but rather reflects a mode of behavior of the material during cutting. Assessments of cutting force should, therefore, specify the conditions of cutting for which they have validity [1].

Many studies have been carried out to evaluate the cutting force in terms of tool life, limiting rate of metal removal, surface finish, and chip shape, etc. The results of some preliminary studies relating to the prospects for optimization of machining processes by indirect monitoring which is commonly obsevation of cut chip obtained during machining. However, it is difficult to expect only reliability of the cuttign force because the shape of chips could be changed by a design of cutting tool. In the extreme precision machining, in particulary, the quantitative evaluation of cutting force would be needed to be able to determine accurately alloy composition and tool shape design for material processing [2-3]. A piezoelectric tool dynamometer, generally used for directly measuring force, delivers signal distortion due to its self-dynamic behavior. In this work, we tried to measure and estimate the machinability of free-cutting Cu alloy such as phosphor bronze alloy quantitatively. The machinability in terms of cutting force was measured by using a piezoelectric tool dynamometer which produces a real-time signal of cutting force data during machining.

2. Experimental procedures

Swaged free-cutting phosphor bronze alloy (cylindrical rod: ϕ34 mm) was used as the experimental material. The chemical composition of the alloy is given in Table 1. Annealing of the alloy was conducted at 700°C for 8h in air. After annealing, tensile tests and cutting force tests were carried out. Flat tensile specimens with gauge section

Table 1 Chemical composition of free-cutting phosphor bronze alloy (wt.%).

	Sn	Pb	Zn	P	Cu
Results	4.32	4.22	2.83	0.15	Bal.

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dimensions of 3×2×13 mm and cutting force specimens with 14×14×80 mm were cut out. The cutting force tests were carried out by using a tool dynamometer with an installed force sensor. Fig. 1 shows the schematic representation of machinability test. The following cutting conditions were employed for measuring cutting force: cutting velocity (V_C) 8,000 mm/min, feed per tooth (f_t) 0.0365 mm, depth of cut (DOC) 0.25 mm, and radial depth of cut (RDC) 3 mm. The measurement of the arithmetic roughness average (R_a) was measured by using laser scanning microscopy (OLS3000). The acquisition of the cutting force data was made by a piezoelectric tool dynamometer (Kistler 9256B1) connected to a control unit, data acquisition board and computer, making it capable to simultaneously measure all orthogonal forces which occur in turning operations (cutting force (F_z), feed force (F_y) and depth force (F_x)), as shown in Fig. 2. The dynamometer which is used (in Fig. 1(b)) in this study is composed of three superimposed piezoelectric layers. These layers are sandwiched under high preload between two thick steel plates. Every layer is cut according to one crystallographic plane. Then the deformation of one of these layers gives a proportional quantity of electric charge in one direction. This quantity is in turn proportional to the delivered signal. When measuring dynamic cutting force, such as those obtained in milling of in turning of a specially designed specimen, the dynamometer will be under forced and free vibration, as shown in Fig. 2. The value of machining force (F_m) was calculated according to the following expression:

$$F_m = \sqrt{F_x^2 + F_y^2 + F_z^2} \tag{1}$$

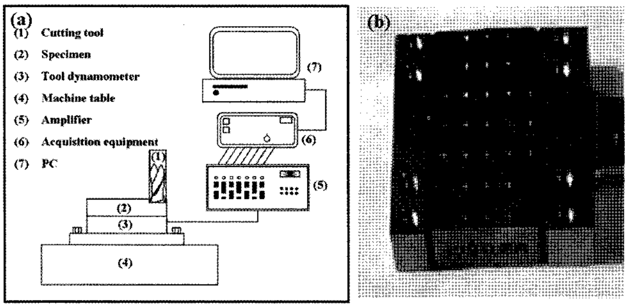

Fig. 1. (a) Schematic illustration of cutting force mesurement system and (b) photograph of tool dynamometer for cutting force measurement used in this study.

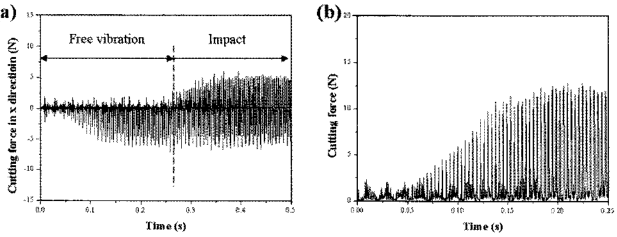

Fig. 2. Signal delivered by tool dynamometer under free vibration and forced. (a) Cutting force in x directioin (b) Cutting force of resultant of x, y, and z direction.

3. Results and discussion

Figs. 3 and 4 show the microstructure of the alloy after annealing at 700°C for 1h and 8h. After annealing, the recrystallizaiton structure was observed. This recrystallization structure is due to stresses imposed during swaging process. We can find the annealing twins in the annealed microstructure. These annealing twins were commonly

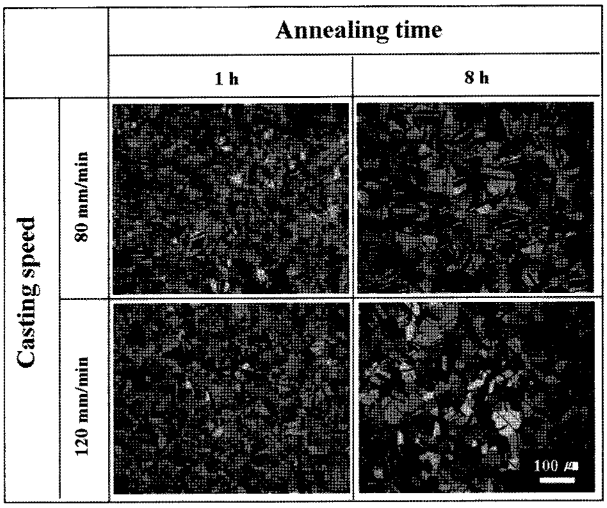

Fig. 3. The influence of annealing time and casting speed on the microstructures of free-cutting phosphor bronze alloy after annealing at 700°C.

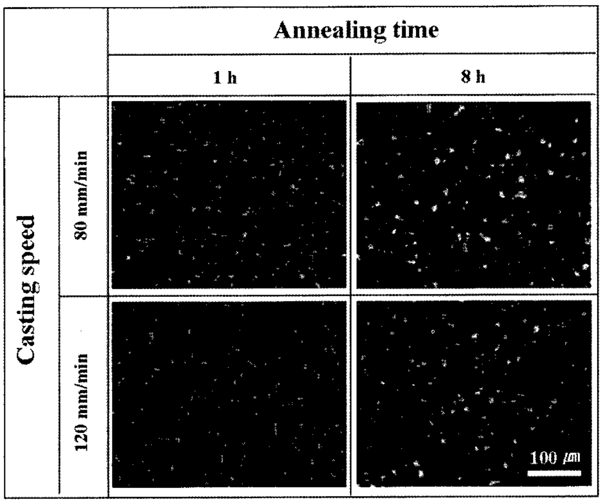

Fig. 4. SEM micrographs showing the growth of lead particles (at 700°C).

observed in the fully recrystallized microstructure of the present materials. It is well known that annealing twins are formed in the recystallized microstructure of fcc materials with a medium or low stacking fault energy (γ_{SFE}) [4]. The zinc acts in a dominant role in decreasing the stacking fault energy (γ_{SFE}) for Cu-Zn alloys [5]. In Figs. 3 and 4, the lead particles were observed on the grain boundary. The lead particles as an insolubility element for Cu-base alloys were trapped by the dendrite arms during casting. During annealing, the lead particles clustered on the grain boundary. After annealing for 8h, the coarse lead particles with a size of $\sim$10 μm could be found on the triple points of the grain boundaries. Besides, a fine-grained two-phase microstructure with fine dispersed small lead particles improves cutting force [6]. To investigate the influence of casting speed, the grain size and lead particle size were measured by using Image pro plus (v. 4.0). Fig. 5 shows the variation of the grain size and lead particle size with annealing time. The grain size and lead particle size gradually increased with increasing annealing time. The growth rate of the recrystallized grains slightly decreased with decreasing casting speed; however, the growth rate of the lead particles slightly increased. There are reasons why these phenomena depend on casting speed. In the case of slow casting speed, the initial structure forms a coarse-grained structure. By contrast, the initial structure was greatly refined in the case of fast casting speed. During the swaging process, the imposed stress was higher in a refined initial structure. Therefore, the growth rate of recrystallized grains greatly increased through use of fast casting speed, as shown in Fig. 5(a). However, this phenomenon is reversed in terms of the growth of lead particles (in Fig. 5(b)). In the case of slow casting speed, the coarse lead particles were formed on the inter-dendrite arms. By contrast, the fine lead particles formed via fast casting speeds were easily clustered on grain boundary during annealing.

Fig. 6 shows the variation of tensile strength and quantitative machinabiliy of the alloy during annealing

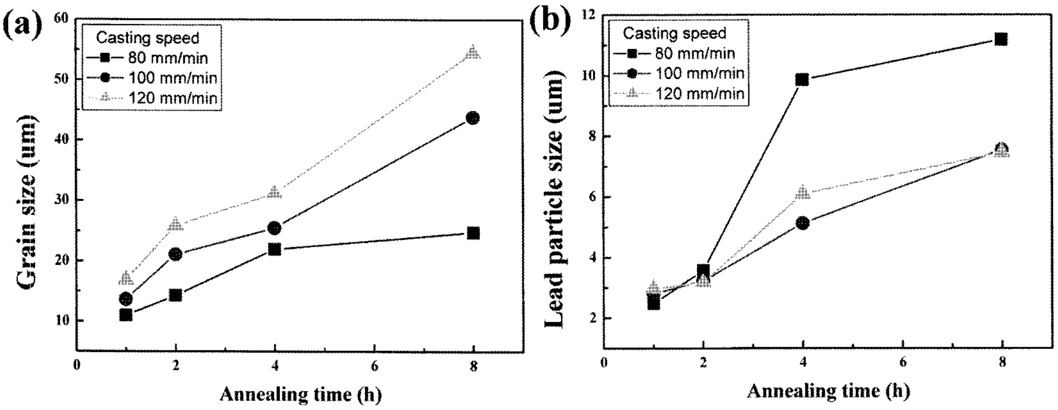

Fig. 5. The influence of annealing time on the grain size and lead particle size of free-cutting phosphor bronze alloy. (a) Variations in grain size with different annealing time. (b) Variationis in lead particle size with different annealing time.

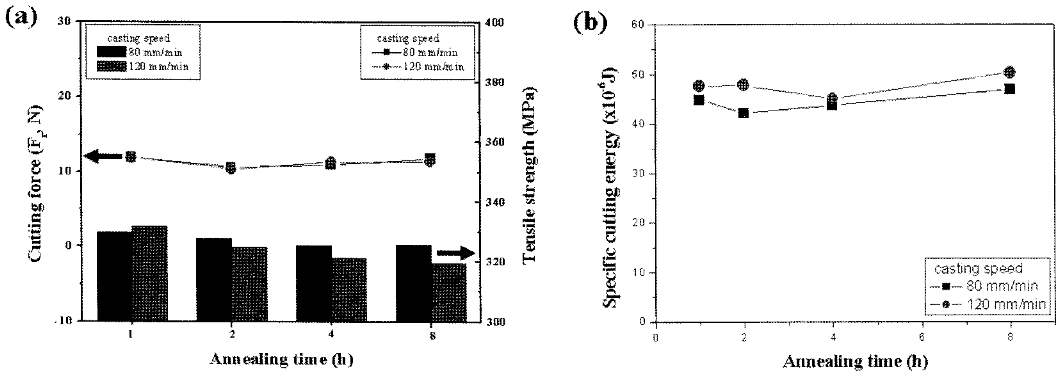

Fig. 6. The influence of annealing time and casting speed on the tensile strength and cutting force of free-cutting phosphor bronze alloy. (a) Variations in tensile strength and cutting force with different annealing time and casting speed (b) Variaitons in specific cutting energy with different annealing time and casting speed.

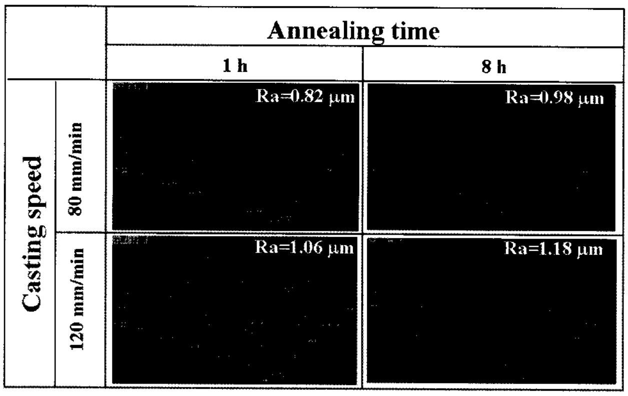

Fig. 7. The influence of annealing time on the surface roughness (Ra) after cutting force test.

process. The tensile strength gradually decreased with increasing annealing time due to grain growth and the clustering of lead particles. The fast softening behavior of the alloy was appeared within high casting speed. From comparing of Figs. 5(a) and 6(a), the grain growth acts as a dominant role in the softening behavior of the alloy. However, the cutting force in terms of machinability (F_m) did not change greatly with annealing time. From Fig. 6, average cutting force (F_m) of ~12 was exhibited. Therefore, the quantitative cutting force in terms of cutting force (F_m) was not affected greatly by grain size and lead particle size. For detail analysis, specific cutting energy was calculated from the cutting force curves of the alloy. Fig. 6(b) shows the variation of specific cutting energy of the alloy with annealing time. The specific cutting energy as calculated from the cutting force curve was not greatly changed with annealing time. Therefore, the specific cutting energy for cutting force of the alloy was not greatly affected by growth of grains and lead particles. Fig. 7 shows the variation of surface roughness (Ra) with annealing time after a cutting force test. After the cutting force test, the surface roughness was not observed to have changed according to annealing time and casting speed. This result agrees with the result of the specific cutting energy test. In all specimens, the surface roughness is below 1.0 um. By comparing with results in existing literature, this value is very low.

4. Conclusions

Both grain growth and lead particle growth induced softening in annealed free-cutting phosphor bronze alloy. Even though the tensile strength was affected greatly by grain growth and lead particle growth, quantitatively cutting force of free-cutting phosphor bronze alloy was not greatly affected by growth in grains and lead particles. The range of cutting force is 11 N to 13 N in the present study. Consequently, it can be mentioned that the most effective variables to improve the machinability of phosphor bronze alloy is not lead particle size and grain size but content of the lead in the alloy.

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