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# Effects of equal channel angular pressing on the strength and toughness of Al–Cu alloys

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**Abstract** Tensile and impact tests were performed on Al–0.63 wt%Cu and Al–3.9 wt%Cu alloys subjected to equal channel angular pressing (ECAP) with different number of passes. Besides the tensile properties, data about the static toughness and the impact toughness were obtained. The strength and the toughness of the Al–Cu alloys were ameliorated and upgraded to a high level collectively. In addition, fracture surface observations show that the fracture behavior of the Al–Cu alloys changes from brittle mode to ductile mode after multi-pass ECAP.

## Introduction

Severe plastic deformation (SPD) has attracted worldwide attention in recent years owing to its capability to substantially refine the coarse-grained metals or alloys down to submicrometer or nanometer level [1, 2]. Several techniques based on SPD, such as equal channel angular pressing (ECAP) [3–7], high-pressure torsion (HPT) [8, 9], dynamic plastic deformation (DPD) [10], and accumulative roll bonding (ARB) [11], have been widely developed to produce ultrafine-grained (UFG) or nanocrystalline (NC) materials. Of these various techniques, ECAP is a promising process because it can produce bulk, fully dense, and contamination-free UFG materials.

ECAP has been applied to various Al alloys, mainly in Al–Mg alloys [12–15]; however, there are few reports on Al–Cu alloys processed by ECAP so far. Murayama et al. [16] studied the microstructure of Al–1.7 at%Cu alloy deformed by ECAP. They used the Al–Cu alloy samples through solution treatment and aging, $\theta$_precipitates were almost completely dissolved after eight passes of ECAP, and nearly single-phase microstructure with a fine grain was obtained. Wang et al. [17] applied ECAP to a lamella Al–33%Cu eutectic alloy, and shear features of the material were investigated. Fang et al. [18] studied the tensile properties and fracture modes of casting Al–Cu alloys applied to ECAP. Recently, wear properties of ECAPed Al–Cu alloys were also reported [19].

One method for strengthening metals without losing toughness is grain refinement, but when the grain sizes fall below ~1 μm, strengthening is usually accompanied by a drop in ductility and toughness [20, 21]. As is well known, UFG materials processed by ECAP often exhibit an enhanced strength, but the ductility is also decreased [1]. However, various materials with high strength and ductility have been obtained after ECAP processing [22, 23]. Besides, nanotwinned Cu with extremely high strength and good ductility has been made via electrodeposition [24]. In contrast, data on toughness of the UFG materials are very limited, because the dimension of the samples processed by ECAP is usually so small that it is difficult to carry out the fracture toughness test.

In this study, tensile and impact tests on Al–0.63 wt%Cu and Al–3.9 wt%Cu alloys subjected to different number of

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ECAP passes were performed. Much attention was paid to the static toughness and impact toughness of the Al–Cu alloys. We try to study the strength and the toughness of the Al–Cu alloys subjected to ECAP by the variation of the static toughness and impact toughness.

## Experimental procedure

Al–0.63 wt%Cu and Al–3.9 wt%Cu ingots are cast. Before ECAP, some billets 10 mm in diameter and 80 mm in length were cut from the ingots by spark cutting technique. Before pressing, the billets were coated with $MoS_2$ as lubricant. These billets were processed by ECAP at room temperature, using a solid die fabricated from tool steel with two channels intersecting at an inner angle of 90°. The rods subjected to repetitive pressing were rotated by 90° in the same direction between each pass in the procedure designated as route $B_C$ [25]· Both alloys were subjected to 1, 2, and 4 passes, respectively. After ECAP, a LEO Supra 35 scanning electron microscope (SEM) and a JEM-2000FX II transmission electron microscope (TEM) were used to investigated the microstructures of as-cast and pressed samples.

Tensile specimens with gauge dimensions of 14 × 3 × 5 mm were machined from the ECAPed samples with their tensile axes lying parallel to the pressing direction. Tensile specimens size are not standard, because the dimension of the samples processed by ECAP is limited. These specimens were subjected to tensile load up to failure at room temperature using an MTS mini testing machine operating at a constant rate of cross-head displacement with a strain rate of about $5 \times 10^{-4}$ $s^{-1}$.

Specimens for impact test were machined from the ECAPed rods along the axial direction. The specimen size is 5 × 5 mm in cross-section and 50 mm in length. The specimens without notch were used to eliminate the effect of notch on the alloys. Impact tests were performed at room temperature using a Zwick/Roell RKP450 testing machine. After tensile and impact tests, the fracture surfaces of all specimens were observed by SEM to study the fracture features.

## Results and discussion

### Microstructures

Figure 1 shows the microstructure of the as-cast alloys. The as-cast Al–0.63%Cu alloy consists of Al solution and dot-like $\theta$ phase ($Al_2Cu$) distributing in the matrix, and the average grain size is about 400 μm, as shown in Fig. 1a. For the as-cast Al–3.9%Cu alloy, the average grain size is about 100 μm. Meanwhile, it is evident that there are many $\theta$ phases precipitated along grain boundaries, forming a net-like morphology (Fig. 1b).

Figure 2 shows the microstructure of the alloys as ECAPed for four passes. It is clear that the Al–0.63%Cu alloy has been refined to submicron meter level by repeated shear deformation. For Al–3.9%Cu alloy, similar grain refinement can also be achieved after four passes of ECAP, forming a microstructure with grain size of about 200–300 nm. In addition, $\theta$ phase in Al–3.9%Cu alloy disperses more uniformly than those of the as-received condition, and had almost been broken into many small disperse particles, as shown in Fig. 2b. This result is consistent with an aluminum 7034 alloy processed by ECAP [26].

### Tensile properties

Figure 3 shows the tensile stress–strain curves of the alloys. The starting points of curves for Al–3.9%Cu are not on zero-engineering strain in order to avoid confusion from overlap of curves. The tensile properties of the present Al–Cu alloys are also summarized in Table 1. According to Fig. 3 and Table 1, it can be seen that there is apparent difference in the mechanical properties of two Al–Cu alloys, due to different Cu content. After each pass of ECAP, the elongation of the Al–0.63%Cu alloy is much higher than that of the Al–3.9%Cu alloy, while the strength of Al–3.9%Cu is obviously higher than that of Al–0.63%Cu alloy. It is clear that the ultimate tensile strength (UTS) of both Al–Cu alloys increases with increasing the number of ECAP passes. The strengthening effect can be attributed to three factors, i.e., grain refinement, high density of dislocations and the dispersion of the broken $\theta$ phase. It also can be seen that the elongation to failure of each alloy varies less after ECAP from one pass to four passes. Moreover, it is of interest to note that the elongation of the Al–3.9%Cu alloy is extremely small even after only one pass of ECAP. Whereas the Al–0.63%Cu alloy shows typical tensile stress–strain curves with elongations range within 10–20%.

According to the tensile stress–strain curves, the static toughness of the Al–Cu alloy specimens subjected to different number of ECAP passes was calculated and shown in Fig. 4. Static toughness is the area surrounded by the tensile stress–strain curve and the strain axis, which can be calculated as [27]:

$$U = \int_{0}^{\varepsilon_f} \sigma d\varepsilon,$$

where $\sigma$ is the flow stress, $\varepsilon_f$is the total strain at fracture. In other words, the static toughness $U$ represents all the plastic

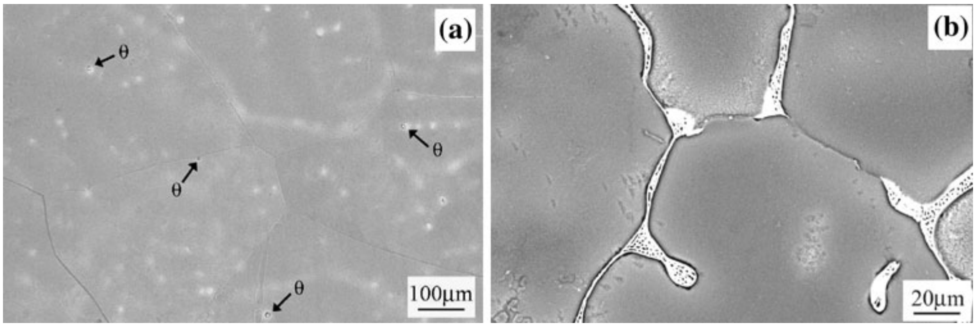

**Fig. 1** Microstructures of the as-cast alloys, **a** Al–0.63%Cu alloy, **b** Al–3.9%Cu alloy

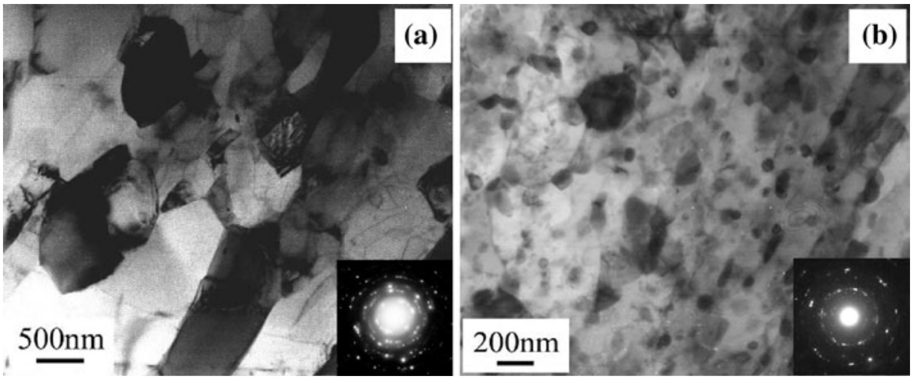

**Fig. 2** TEM micrographs of the alloys ECAPed for four passes, **a** Al–0.63%Cu alloy, **b** Al–3.9%Cu alloy

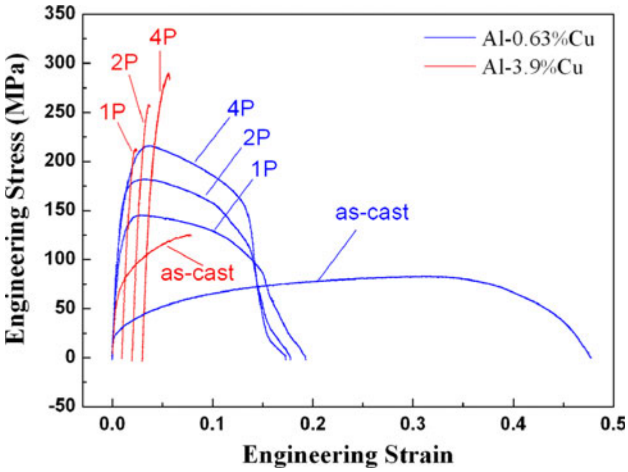

**Fig. 3** Tensile stress–strain curves of Al–0.63%Cu alloy and Al–3.9%Cu alloy

work absorbed by the unit volume of the tensile samples during the whole plastic deformation process up to fracture. Static toughness is an important concept representing the toughness of materials [27]. It can be seen from Fig. 4 that the static toughness of the Al–0.63%Cu alloy is much larger than that of the Al–3.9%Cu alloy, and that the static toughness of the two alloys decreases after one pass, thereafter increases with increasing ECAP passes. After four passes, the static toughness of the samples is quite close to that of the as-cast samples. This indicates that the static toughness of the alloys can be improved with increasing the number of ECAP passes. Similar results have also been obtained in a Cu–Ag alloy processed by ECAP via route A [28].

## Impact properties

Figure 5a–b shows the morphology of Al–0.63%Cu and Al–3.9%Cu alloy specimens after impact test, respectively. It can be seen that the Al–0.63%Cu alloy specimens only bend considerably (Fig. 5a), which indicates that the alloy is still ductile even after four passes, and this is corresponding to the high tensile elongation as shown in Fig. 3. In contrast, the fracture mode of the Al–3.9%Cu alloy specimens is different (Fig. 5b), and they finally broke into

**Table 1** Tensile properties of the Al–Cu alloys subjected to different number of ECAP passes

| | Al–0.63%Cu | | | | Al–3.9%Cu | | | |
|---|---|---|---|---|---|---|---|---|
| Number of ECAP passes | 0 (as-cast) | 1 | 2 | 4 | 0 (as-cast) | 1 | 2 | 4 |
| UTS (MPa) | 83.2 | 145.6 | 182.1 | 216.2 | 125.7 | 213.6 | 258.3 | 290 |
| Elongation to failure (%) | 47.8 | 19.4 | 17.8 | 17.3 | 7.8 | 1.5 | 1.7 | 2.7 |

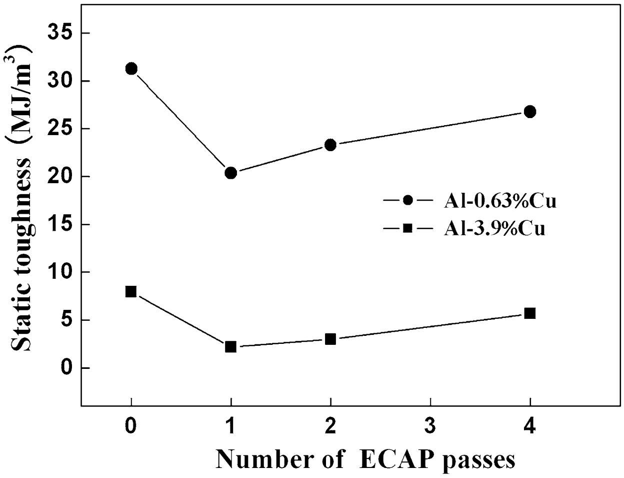

**Fig. 4** Dependence of static toughness of Al–Cu alloys on the number of ECAP passes

two pieces after ECAP, So the Al–3.9%Cu alloy is intrinsically brittle. Therefore, different Cu content of the two alloys results in the difference in the fracture mode of impact samples. For the tensile specimens of the two alloys processed by ECAP, the shear fracture angles are different, and the fracture mode was analyzed and discussed previously [18].

The absorbed energy of the specimens during impact tests is shown in Fig. 6. It is clear that Al–0.63%Cu alloy specimens can absorb more energy than Al–3.9%Cu alloy specimens during impact tests. The absorbed energy of the two Al–Cu alloy specimens increase from one pass to four passes. It is evident that the variation of the impact toughness with the number of ECAP passes is similar to the static toughness for the two alloys.

## Fracture surface observations

Figure 7 shows the fracture surface of the Al–3.9%Cu alloy specimens after tensile test. The as-cast alloy specimen shows a rough fracture surface, and displays a brittle fracture mode, as shown in Fig. 7a. For the specimen ECAPed for one pass, the fracture surface appears finer, compared to that of the as-cast specimen; however, brittle character can also be seen in many areas (Fig. 7b). After two passes, it can be seen from Fig. 7c that the fracture surface of the specimen consists of numerous elongated dimples, so the fracture shows ductile character. After four passes, the alloy specimen shows a fine and homogeneous fracture surface with many equiaxed dimples, as shown in Fig. 7d, so it is very clear that the specimen fractures in a ductile mode.

Figure 8 shows the fracture surface of the Al–3.9%Cu alloy specimens after impact test.

These micrographs show almost the same characteristics with those obtained after tensile tests. For the as-cast specimen and the specimen ECAPed for one pass, it can be seen that the fracture surface shows rough and brittle feature, as shown in Fig. 8a–d. While after two and four passes, the specimens show fine and homogeneous fracture surface with many dimples (Fig. 8e–h).

Based on the observations, it is suggested that the fracture of the alloys changes from brittle mode to ductile mode by multi-pass ECAP. This should be related to the transition of the microstructures caused by ECAP. The microstructure of as-cast alloy consists of large grains and coarse $\theta$ phase, while $\theta$ phase was broken into small dispersed particles after multi-pass ECAP, thus ultrafine-grained and homogeneous microstructure was obtained.

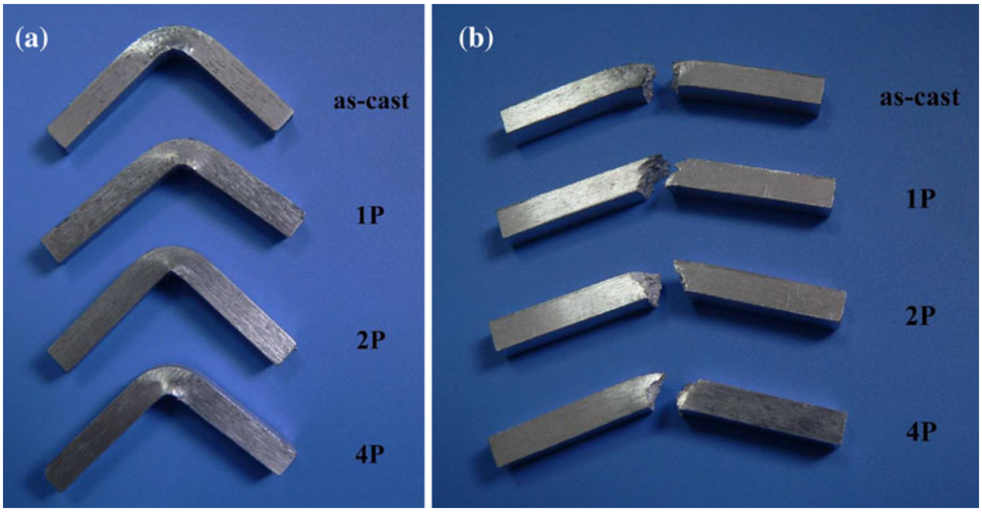

**Fig. 5** Morphology of Al–Cu alloys specimens subjected to different number of ECAP passes after impact test, **a** Al–0.63%Cu alloy, **b** Al–3.9%Cu alloy

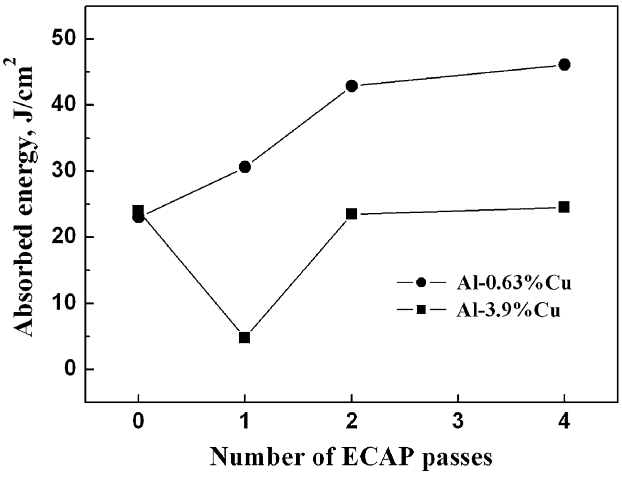

**Fig. 6** Dependence of impact absorbed energy of Al–Cu alloys on the number of ECAP passes

Therefore, it demonstrates that ECAP process can change the alloys from brittle to tough one, although ECAP decreases the elongation of the alloys.

## Strength and toughness of Al–Cu alloys

Several studies on the toughness of ECAPed materials can be found. Somekawa et al. [29] once reported the fracture toughness of Mg–Al–Zn alloy processed by ECAP. In their study, the specimens were extruded at 503 K for eight passes, and then tensile test and plane-strain fracture toughness test were carried out. Their results indicate that the ductility was considerably improved while tensile strength decreased, and the fracture toughness, $K_{IC}$, was also improved. Purcek et al. applied ECAP to Zn–40%Al alloy [30] (processed at 130 °C) and Al–40% Zn alloy [31] (processed at 90 °C), and investigated the tensile and impact properties. They found that the elongation of the two alloys increased while their strength decreased after multi-pass ECAP, and the impact toughness of the alloys was improved due to the significant increase in ductility. In addition, Ma et al. applied rotary-die ECAP (RD-ECAP) to Al–11%Si [32] and Al–23%Si [33] alloys at high temperatures, and found that the impact toughness increased markedly with a greater number of RD-ECAP passes.

In the above-mentioned studies, little attention was paid to the relationship between strength and toughness of ECAPed materials. Wetscher et al. [34] reported the mechanical properties of pearlitic steel R260 deformed by ECAP at room temperature. According to their results, the strength of the steel was increased after ECAP, while the increase or decrease of the fracture toughness depended on the orientation of the crack relative to the aligned microstructure.

The present tensile and impact tests provide some data about the tensile strength, static toughness and impact toughness of the Al–Cu alloy specimens subjected to different number of ECAP passes. According to the results above, the relationship between tensile strength and the toughness can be further discussed in detail as below.

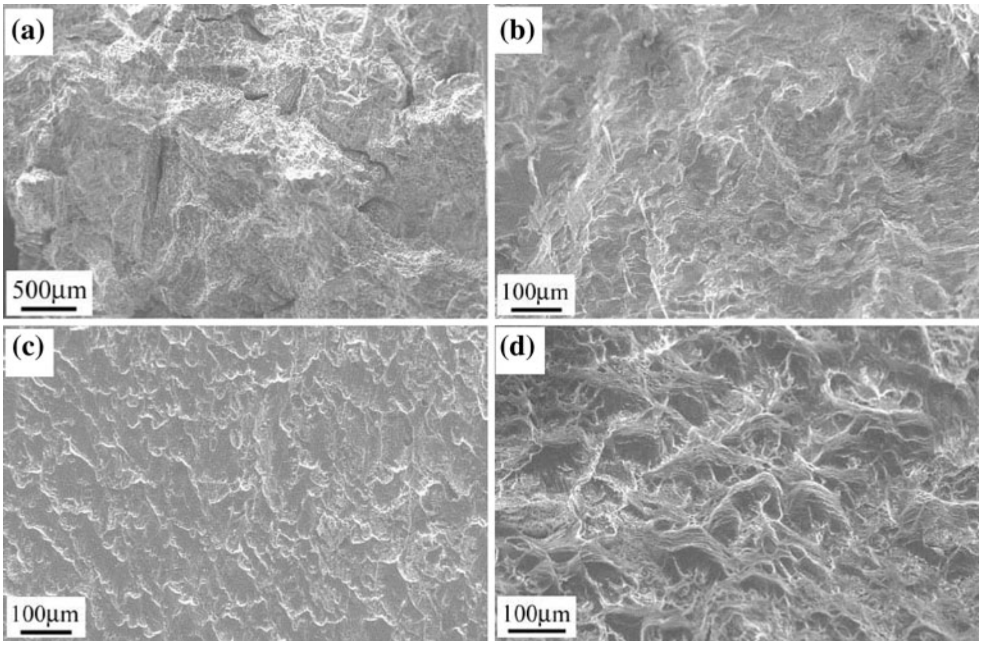

**Fig. 7** SEM micrographs of fracture surfaces of the Al–3.9%Cu alloy specimens after tensile test, **a**: as-cast, **b**: ECAPed for 1 passes, **c**: ECAPed for 2 passes, **d**: ECAPed for 4 passes

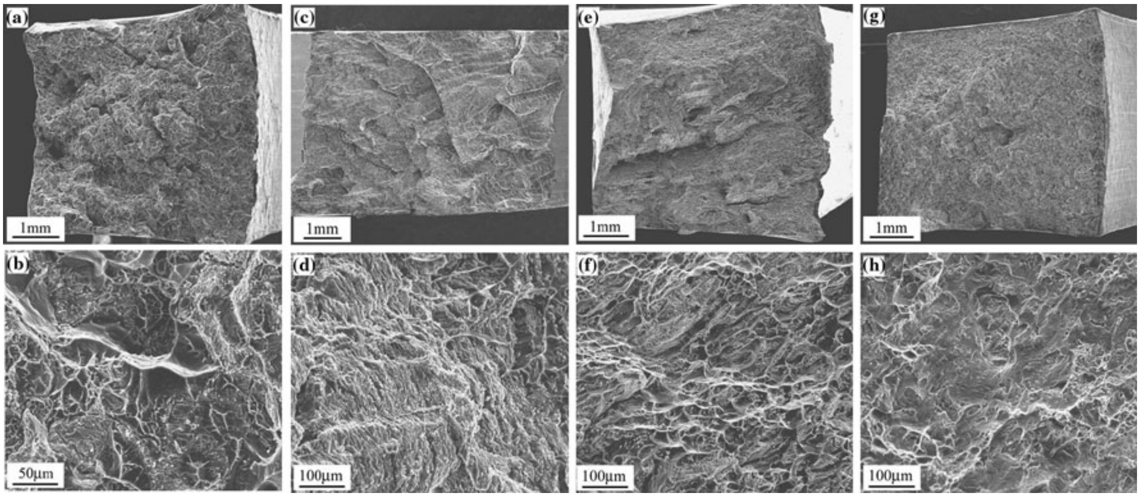

**Fig. 8** SEM micrographs of fracture surfaces of the Al–3.9%Cu alloy specimens after impact test, **a** and **b**: as-cast, **c** and **d**: ECAPed for 1 passes, **e** and **f**: ECAPed for 2 passes, **g** and **h**: ECAPed for 4 passes

The relationship between the static toughness and the UTS is shown in Fig. 9. It can be seen that the static toughness and the ultimate tensile strength of the two Al–Cu alloys upgrade collectively when conducted by ECAP from one pass to four passes. Figure 10 shows the dependence of impact toughness of Al–Cu alloys on tensile strength. Similarly, the impact toughness and tensile strength increase at the same time from one pass to four passes. The results demonstrate that ECAP is very effective in simultaneously improving the strength and toughness of the Al–Cu alloys. In Al–11%Si alloy [32] subjected to ECAP, the improved impact toughness is supposed to related to the breakage of the large aluminum dendrites and interdendritic networks of eutectic silicon in the first several passes, the modified grain or grain fragment boundaries, the ultrafine grains or grain fragments, the content of fine particles and the homogenized microstructure resulting from multi-pass RD-ECAP. In relation to the great grain refinement and breakage of the $\theta$ phase, it is not surprising that the impact toughness increases with the number of ECAP passes.

It is known that the strength and toughness of the Al–Cu alloys can be improved by multi-pass ECAP, but their elongation was obviously deteriorated. Recently, some researchers reported that the strength and the ductility will be simultaneously upgraded if profuse twins and stacking faults are introduced by the deformation or grow-in methods [22, 24, 35, 36]. For example, Qu et al. found that the strength and ductility increase with decreasing the stacking fault energy of Cu–Al alloy when processed by ECAP [36]. It is suggested that ECAP is a promising method in adjusting the comprehensive mechanical properties among strength, ductility, and toughness of materials.

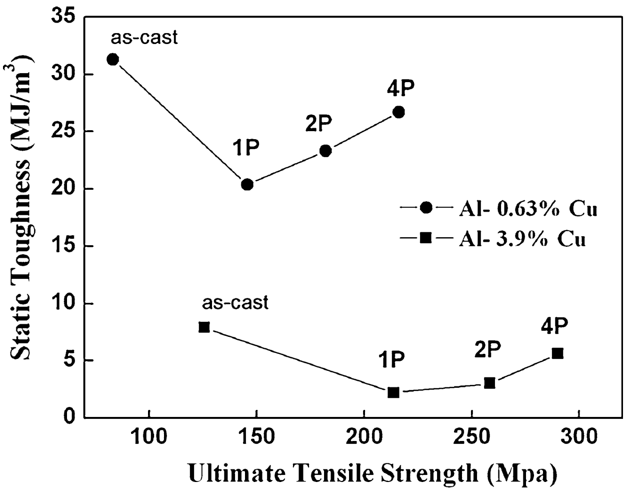

**Fig. 9** Dependence of static toughness of Al–Cu alloys on tensile strength

## Conclusions

Tensile and impact tests on Al–0.63%Cu and Al–3.9%Cu alloys subjected to different number of ECAP passes were performed; the results are summarized as follows.

(1) The grains of Al–Cu alloys were refined to submicron level after multi-pass ECAP. In Al–3.9%Cu alloy, the precipitate phase $\theta$ along grain boundaries can be broken into small disperse particles after ECAP.

(2) Tensile and impact fracture surface observations show that fracture behavior of the Al–Cu alloys changes from brittle to ductile mode by multi-pass ECAP.

(3) The static toughness and impact toughness of the Al–Cu alloys are improved with increasing the number of

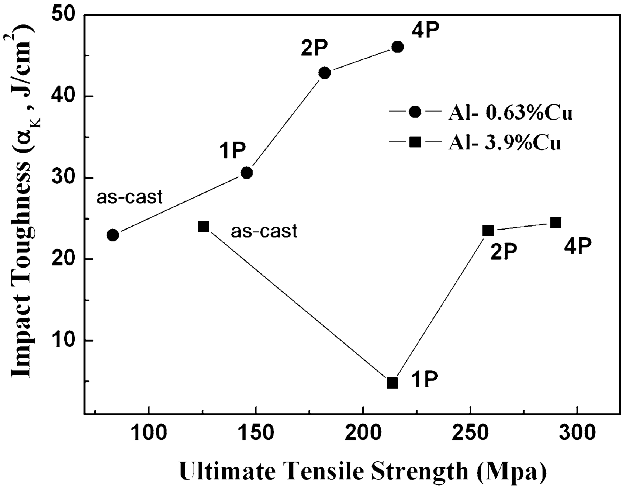

**Fig. 10** Dependence of impact toughness of Al–Cu alloys on tensile strength

ECAP passes. The results demonstrate that ECAP is very effective in improving the strength and toughness of Al–Cu alloys simultaneously.

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