J Mater Sci (2007) 42:5476–5482
DOI 10.1007/s10853-006-0883-0

Recrystallization and fracture characteristics of thin copper wire

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Received: 22 March 2006 / Accepted: 23 August 2006 / Published online: 3 April 2007

Abstract In this study, the annealed effect (at 150 °C ~ 250 °C for 1 h) on the tensile mechanical properties of thin copper wires with $\phi = 25\ \mu$m (1 mil) was investigated. The microstructural characteristics and the mechanical properties before and after an electric flame-off (EFO) were also studied. Results indicate that with annealing temperatures of more than 200 °C, the wires possessed a fully annealed structure, the tensile strength and the hardness decreased, and the elongation was raised significantly. Through recrystallization, equiaxed grains and a few annealed twins formed in the matrix structure. The microstructures of the free air ball (FAB) of the various wires after EFO contained column-like grains. The column-like grains grew from the heat-affected zone (HAZ) to the Cu ball, and the preferred orientation was <100>. According to Weibull's reliability analysis, the failure rates of all the specimens were the modus of wear-failure. The tensile strength and the reliability of both the 200 °C and 250 °C annealed wires in the HAZs showed the highest values of all.

Introduction

Gold wire and copper wire are the preferred interconnect materials to bond with aluminum metallized wafer pads [1, 2]. Notably, gold is expensive, and the electrical conductivity and thermal conductivity of gold is lower than that of copper [3, 4]. In addition, the inherent properties of higher tensile strength, hardness and stiffness of copper as well as its cost effectiveness compared to gold, have made it a preferred alternative [3, 5].

In general, three factors affect the reliability of copper wire bonding [3, 6] namely: (1) Oxidation causing unusual bonding, (2) The lower strength of the annealed wire resulting in breakage, (3) The high hardness of copper wire damaging chips during the wire compressing process. As-drawn copper wire possesses higher strength and hardness, however its lower ductility reduces the reliability of bonding. So, the annealing treatment of as-drawn copper wire is very important. Many studies [2, 3, 6] have discussed the process variables such as bonding force, temperature and electric flame-off (EFO), etc. However, the recrystallization characteristics in the microstructure and the relevant mechanical properties of thin copper wires ($\phi = 25\ \mu$m) have still not been examined, and in particular, the reliability of wires in the heat-affected zone (HAZ).

In addition, because the breakage sites of EFO wires are in the neck between the HAZ and the ball, it's clear that the breakage results from the structure of the neck zones and stress affecting the breakage sites [2, 6, 7]. Thus, this paper not only investigated the mechanical properties of copper wires and the free air ball (FAB), but also investigated Weibull's reliability of the tensile strength in FAB with various annealing wires using the EFO process.

Experimental procedure

Annealing treatment and electric flame-off (FEO) process

A copper ingot of 99.99% purity was drawn to thin copper wire with diameter $\phi = 25\ \mu$m (ICP analysis of the

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chemical composition is shown in Table 1). Four temperatures, 100 °C, 150 °C, 200 °C and 250 °C, were chosen for the vacuum (10^{-3} Pa) annealing in the as-drawn wire. The annealing time for the as-drawn wires was fixed at 1 h, and followed by air cooling to room temperature. The melting of the wire tip was controlled by EFO using a thermosonic wire bonder. To prevent oxidation during the ball-formation process, a 95% nitrogen and 5% hydrogen gas mixture was maintained at a flow rate of 1 L/min.

Property testing and Weibull's reliability analysis

To understand the effects of annealing on the mechanical properties of the Cu wire, both annealed and unannealed wires were subjected to tensile testing, after which the relation between the mechanical properties and recrystallization was investigated. In addition, the neck of each Cu ball with various annealing wires was also subjected to tensile testing to examine the characteristics of the HAZ and Weibull's reliability. The testing method used a plate clamp to fix the FAB, while the wire tip was fixed using a tongs-like clamp. A schematic illustration of the tensile test is shown in Fig. 1. The copper wire had a diameter of ϕ = 25 μm and length of 10 cm. During the tensile test, each wire was under a constant strain rate of 2.54 cm/min and each analysis datum is the average of 20 test results (including the neck of the Cu ball). Micro-hardness measurements were performed on a cross section of the unannealed copper wire, the ball and the HAZ. The force was 5 g and the holding time was 10 s. An illustration (including the electric flame-off wire) of the hardness testing setup is shown in Fig. 2. Each analysis datum is the average of at least 10 test results.

With an aim to understanding the tensile reliability of the FAB, a statistical method, the Weibull distribution function [8], was applied to evaluate the reliability of the ultimate tensile strength (UTS). The reliability $R(\sigma)$ of materials can be described by the relation $R(\sigma) = 1-F(\sigma)$, where $F(\sigma)$ is the failure rate. There were 20 specimens (n = 20) for tensile strength measurement.

Results and discussion

Microstructures and mechanical properties of thin copper wires

The cross-section microstructures of the annealed and unannealed wires are shown in Fig. 3. The structure of the as-drawn wire contained long, thin grains parallel to the direction of unannealing (Fig. 3a). Both the 100 °C and 150 °C annealed wires are similar to Fig. 3a. The microstructures of both the 200 °C and 250 °C annealed wires are shown in Fig. 3b and Fig. 3c, notably revealing the two copper wires contained fully annealed equiaxed grains and a few annealed twins.

Table 1 ICP analysis of the chemical composition of Cu wire (ppm)

Si	Fe	Mn	Ni	Zn	Ti	Pb	Sn	Cu
0.45	0.05	0.22	0.08	0.10	0.06	0.53	0.07	Bal.

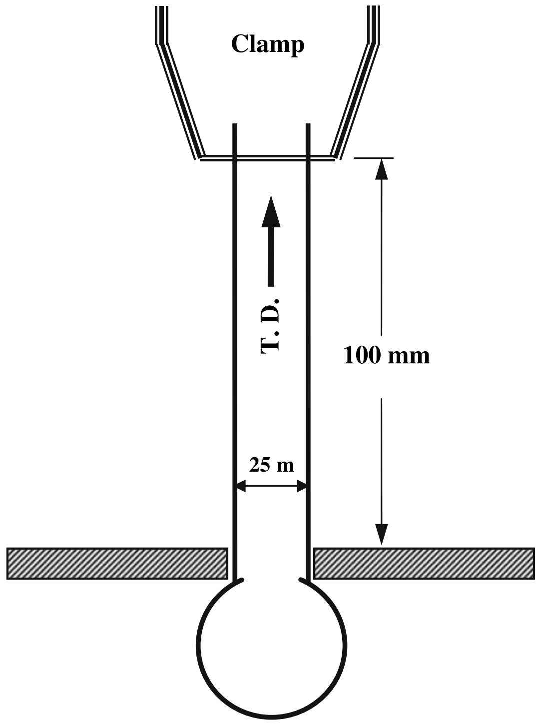

Fig. 1 The schematic illustration of the tensile testing for the neck

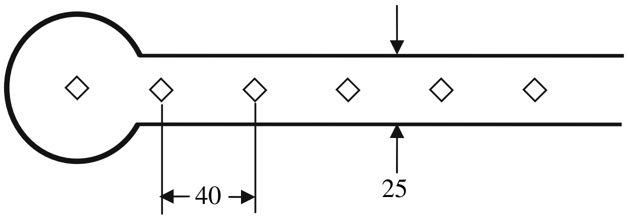

Fig. 2 The schematic illustration of the micro-hardness measuring (unit: μm)

Figure 4 shows the tensile test results of the copper wires with various annealing temperatures. The 100 °C wire and the unannealed wires were similar with a low elongation (T.E.) of less than 1%. When the annealing temperature was 200 °C, both U.T.S. and Y.S. decreased and the elongation raised significantly (~15%). At an even higher annealing temperature of 250 °C, the results were still similar to those of the 200 °C wire. Notably, the 200 °C wire possessed a fully annealed structure (Fig. 3b) and higher ductility. It can be inferred from what has been

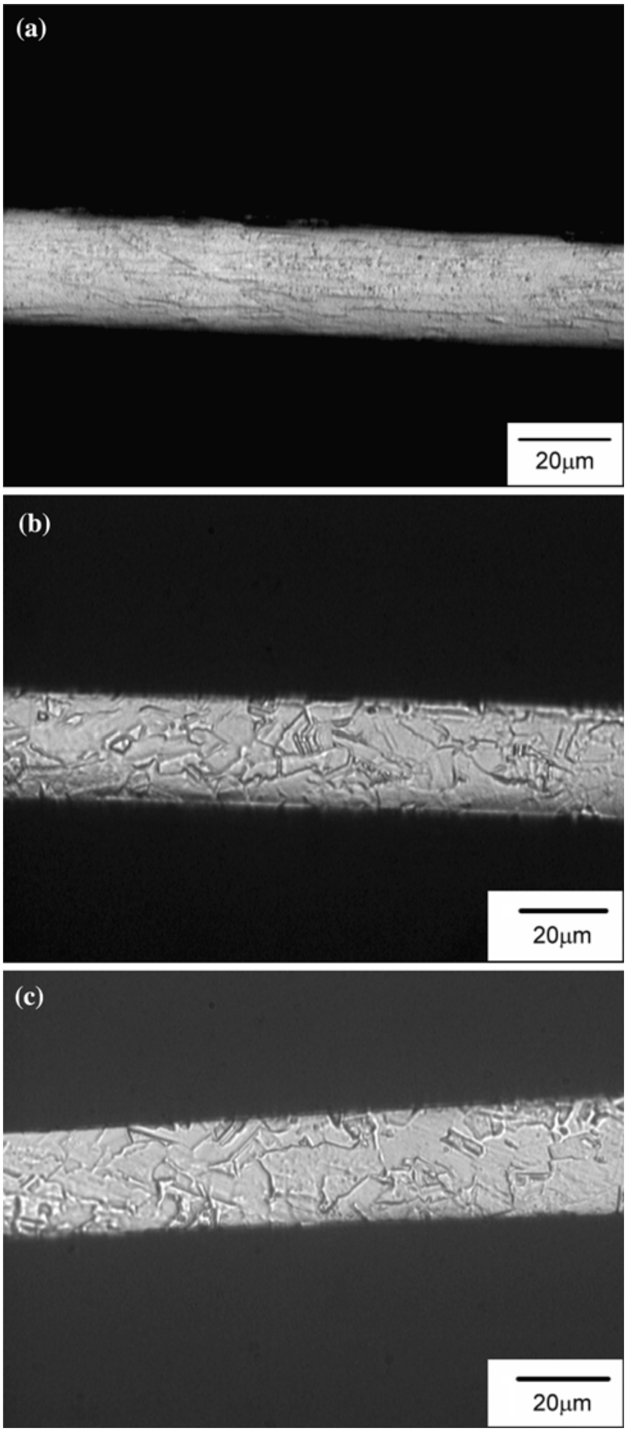

Fig. 3 Microstructures of the annealed wires at different temperature for 1 h: (**a**) unannealed, (**b**) 200 °C and (**c**) 250 °C

said above that a temperature of ~200 °C is probably the recrystallization temperature of the as-drawn wire. To investigate further, micro-hardness was measured on the cross section of the copper wires, as shown in Fig. 5. Results show that the hardness had a tendency towards strengthening. The hardness of the annealed wires was much lower compared with the unannealed wire. So, we can safely assume that the recrystallization temperature of the unannealed wire was ~200 °C.

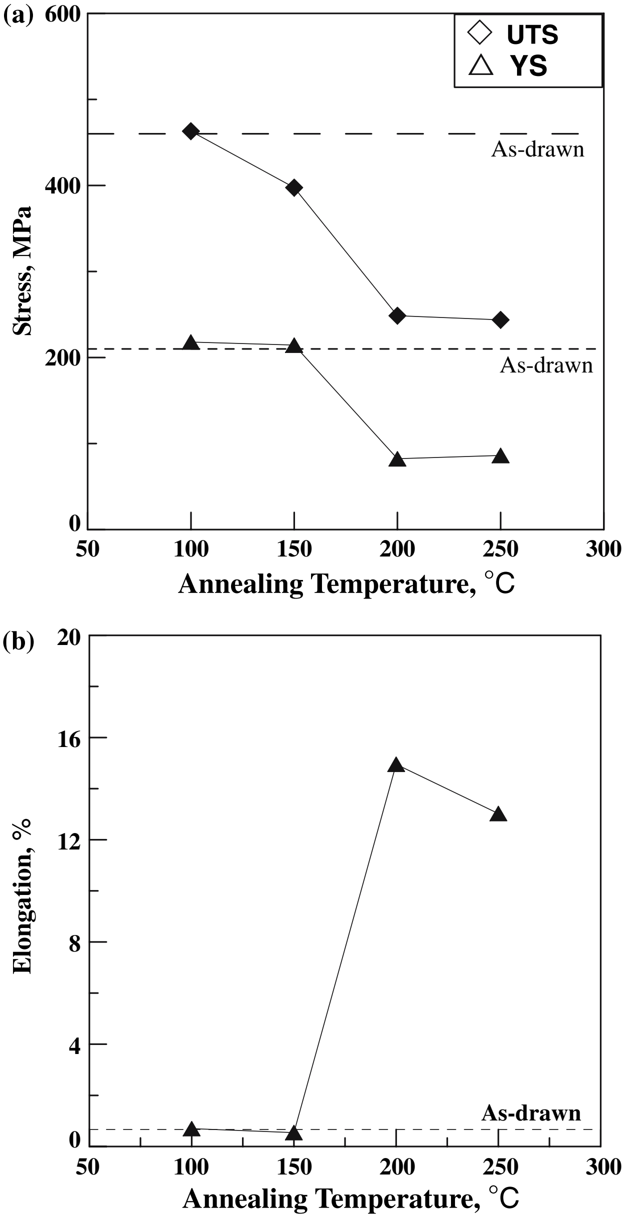

Fig. 4 Tensile properties of wires with various annealing temperature: (**a**) tensile strength and (**b**) elongation

Electric flame-off (FEO) characteristics and tensile analysis of the Cu ball

To understand the tensile strength of the neck, the copper balls of the unannealed wire and the annealed wires was measured, as shown in Fig. 6. The EFO process weakened the neck strength of the balls (Fig. 4). In addition, the average strength of the necks of the Cu balls had a

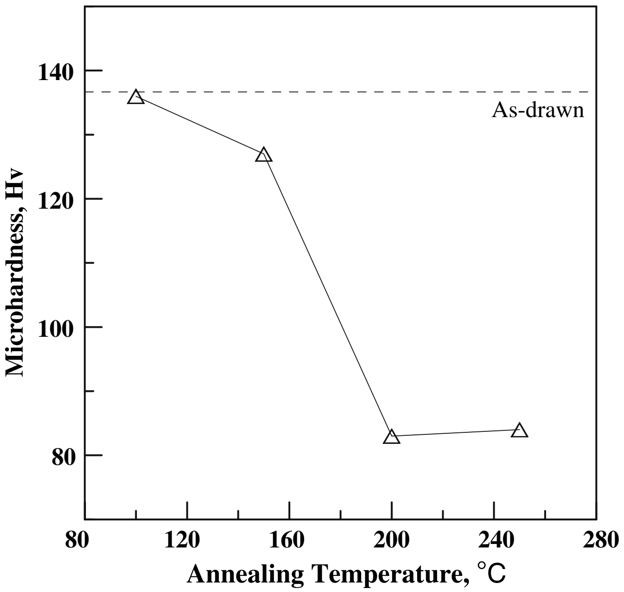

Fig. 5 Micro-hardness of wires with various annealing temperature

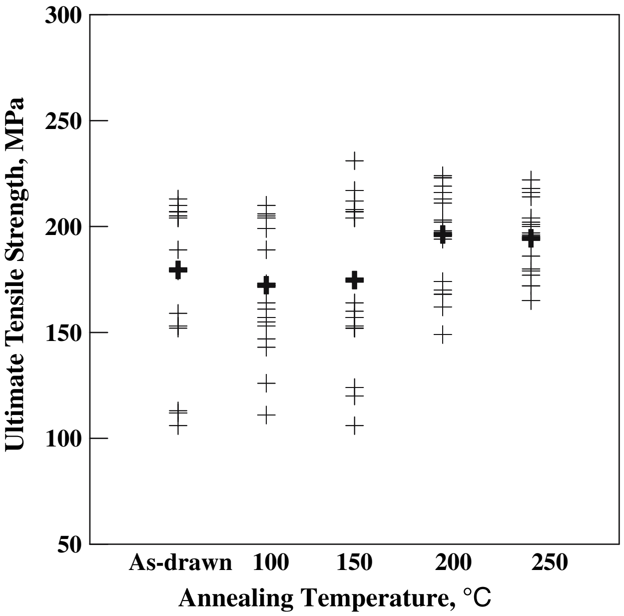

Fig. 6 The ultimate tensile strength (UTS) of the neck of balls

tendency to increase with increasing the annealing temperature. Results show that the balls of the fully annealed wires (above 200 °C) possessed greater neck-strength, and the data tended to be less extreme (Fig. 6). This highlights the importance of neck-strength reliability. Notably, regardless of the annealing conditions, the breakage site of the EFO wires was always at the back of the neck, not at the back of the ball (Fig. 7), revealing that structural variations from the EFO process affected the deformation resistance of the neck zone.

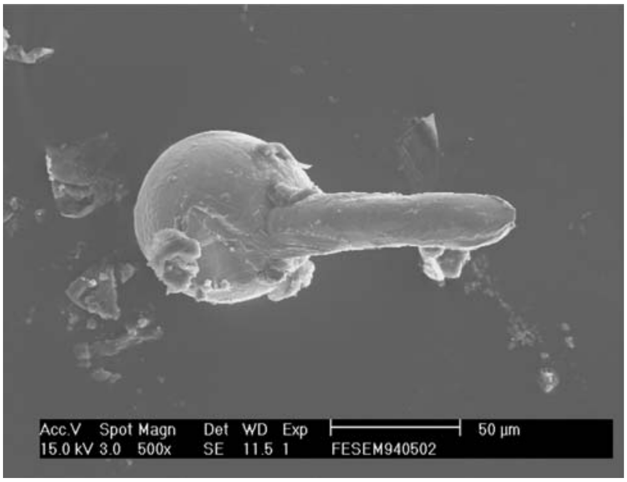

Fig. 7 Tensile fracture feature of the EFO wires. (Take 150 °C annealed wire for example)

EFO mechanism and breakage site

The cross-section microstructure of the FAB of the 200 °C annealed wire is shown in Fig. 8a. The ball structure contained isotropy column-like grains, while the grains of the neck had been induced to grow by heat. The FAB of the unannealed wire was photographed, as shown in Fig. 8b. In addition to the appearance of isotropy column-like grains, the necks of the Cu balls underwent recrystallization during the EFO process. Through this recrystallization, the matrix structure transferred from its original long-thin grains (Fig. 3a) to equiaxed grains and a few annealed twins.

The microstructure of the wire after the EFO can be divided into a solidification zone (i.e., the copper balls), a HAZ induced by the EFO, and an unaffected zone. Fig. 8 shows that continuous interfaces with no void were found between the balls and the heat affect zone. So, it is safe to say that the column-like grains of the ball grew from the HAZ (i.e., the without-solidification wire) to the melting ball. The normal direction of the twinning plane of a fcc twin is <111> and the preferred orientation of the solidification dendrite is <100>. The included angle of the above-mentioned two directions was 54°. We then measured the included angle between the grown-direction of the column-like grains and the normal direction of the twinning plane to be about 54° (Fig. 8b). This also confirms that the preferred orientation of the isotropy column-like grains was <100>.

Additionally, micro-hardness analysis of the 200 °C annealed wire after EFO revealed that the neck of the FAB (i.e., HAZ) had the lowest value (Fig. 9). Also, it can be seen from Fig. 9 that the hardness had a tendency to increase when this zone was far away from the HAZ. Comparing the 200 °C data of Fig. 5 with Fig. 9, the

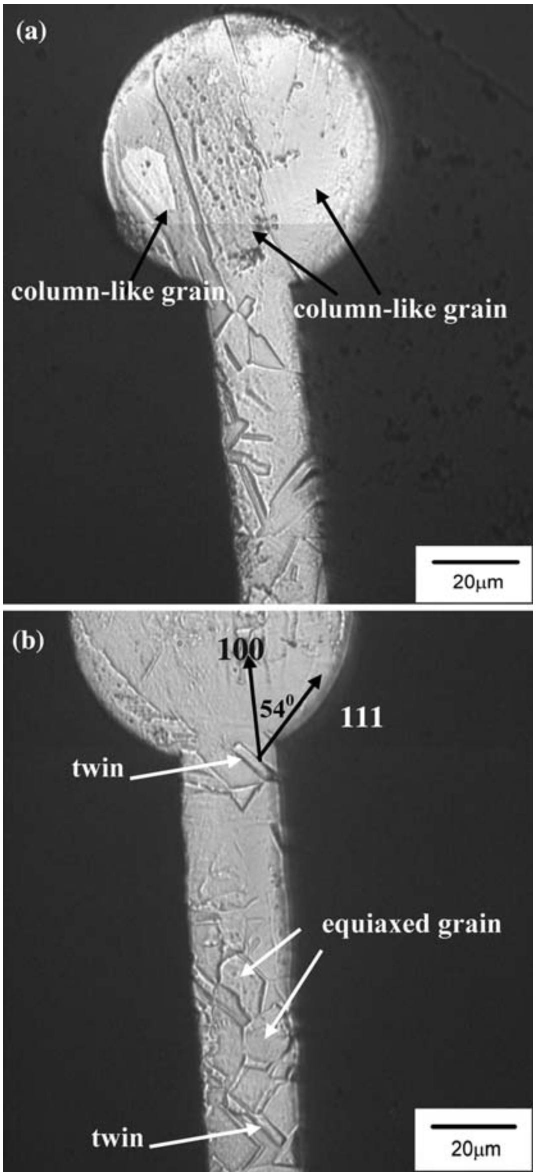

Fig. 8 The cross section of the FABs: (**a**) 200 °C and (**b**) unannealed

hardness increased significantly with lengths of less than 300 μm. Notably, the unannealed wire and the annealed wires also experienced changes similar to these mentioned above. So, it can be inferred that the HAZ had a length of about 300 μm. According to Fig. 7, the breakage site of the EFO wires should be in the HAZ. This is one reason why the breakage sites occurred within 300 μm of the neck.

The UTS of both the neck and the without-EFO wire were compared, as shown in Fig. 10. The strength of the neck was lower than that of the without-EFO wires. This is because the heat effect induced by the EFO process reduced the deformation resistance of the HAZ. In addition, the breakage site of the EFO wires occurred in the HAZ. Clearly, the deformation resistance of the HAZ was lower than that of the neck of the solidification ball. Even though the neck of the solidification ball experienced a stress concentration effect and the appearance of column-like grains, its deformation resistance was still higher than the HAZ.

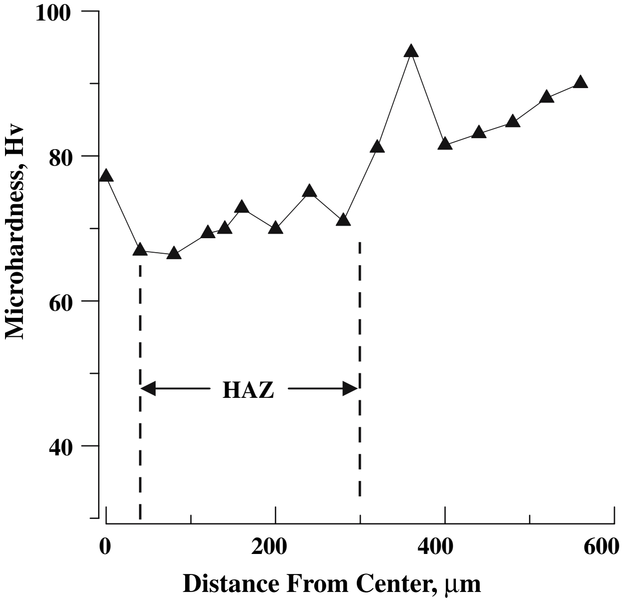

Fig. 9 Micro-hardness of the 200 °C annealed wire after EFO process (the origin of the cross axle is the center of FAB)

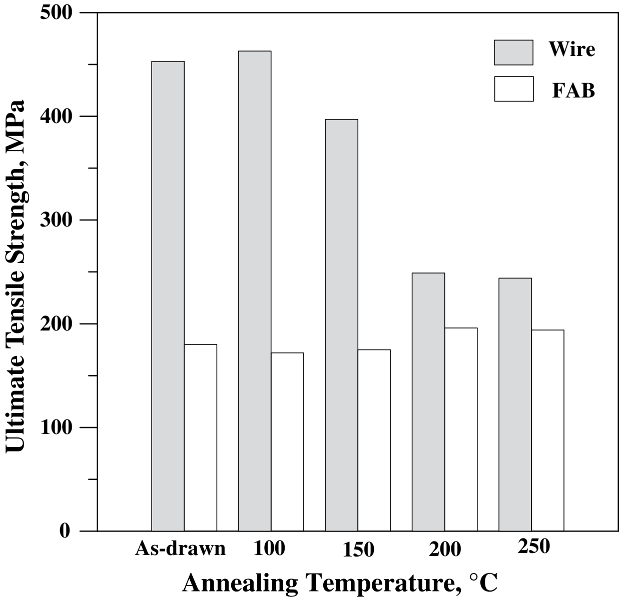

Fig. 10 The comparison of the ultimate tensile strength: the neck of balls and the without-EFO wires

Weibull analysis of the heat-affected zone (HAZ)

Weibull data of the UTS on the HAZ are shown in Fig. 11. In Fig. 11(a), the stress curves of both the 200 °C and 250 °C annealed wires reveal a tendency of centralized distribution, and the peaks of both curves also are higher stresses. This shows that both the 200 °C and 250 °C annealed wires suffered breakage easily at a particular stress. From Fig. 11(b), we see that the failure rates of all the wires are of the modus of wear-failure (Increasing Failure Rate) [8–11], and the failure rates had a tendency to increase with increasing the stress. Notably, under an identical stress in Fig. 11(c), both the 200 °C and 250 °C annealed wires had higher reliability than the other wires.

Due to the reliability of the as-drawn wire being similar to that of the annealed wires (below 200 °C, Fig. 11(c)), it’s grain size was compared with the 200 °C annealed wire in HAZ to understand the difference in reliability. Figure 12 shows that the distribution of grain size for the annealed wire had a more centralized distribution. So, it is safe to say that recrystallization not only induced microstructural changes, but also affected the reliability data in this system.

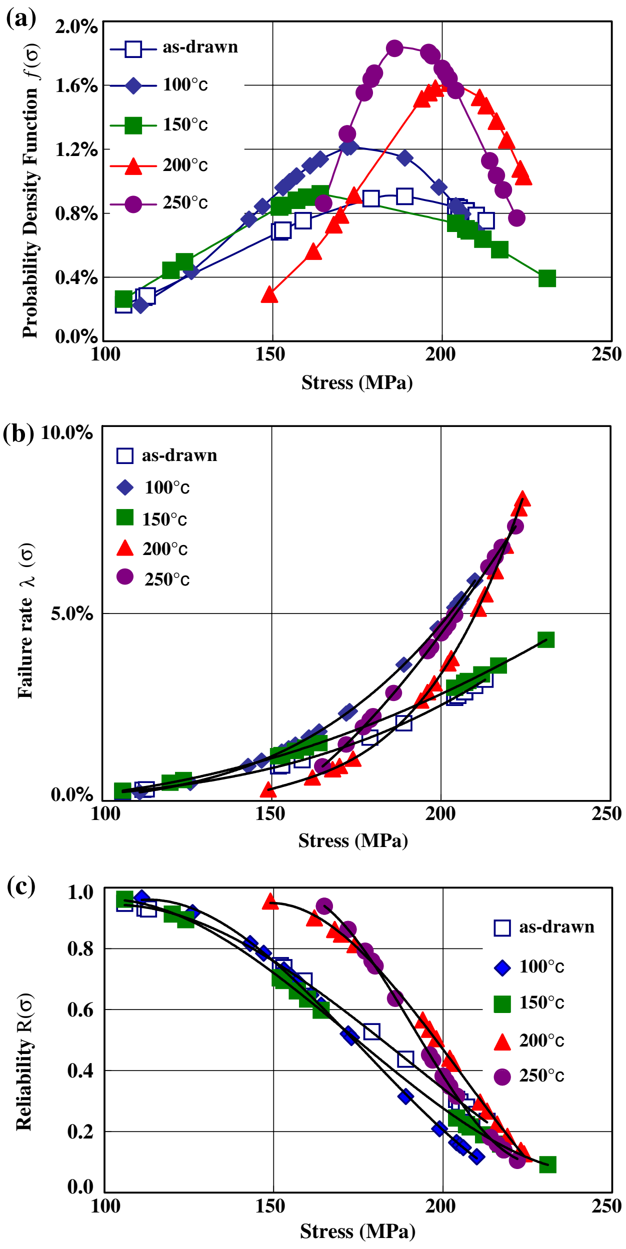

Fig. 11 Weibull analysis of the tensile data on the HAZ: (a) probability density function, (b) failure rate and (c) reliability

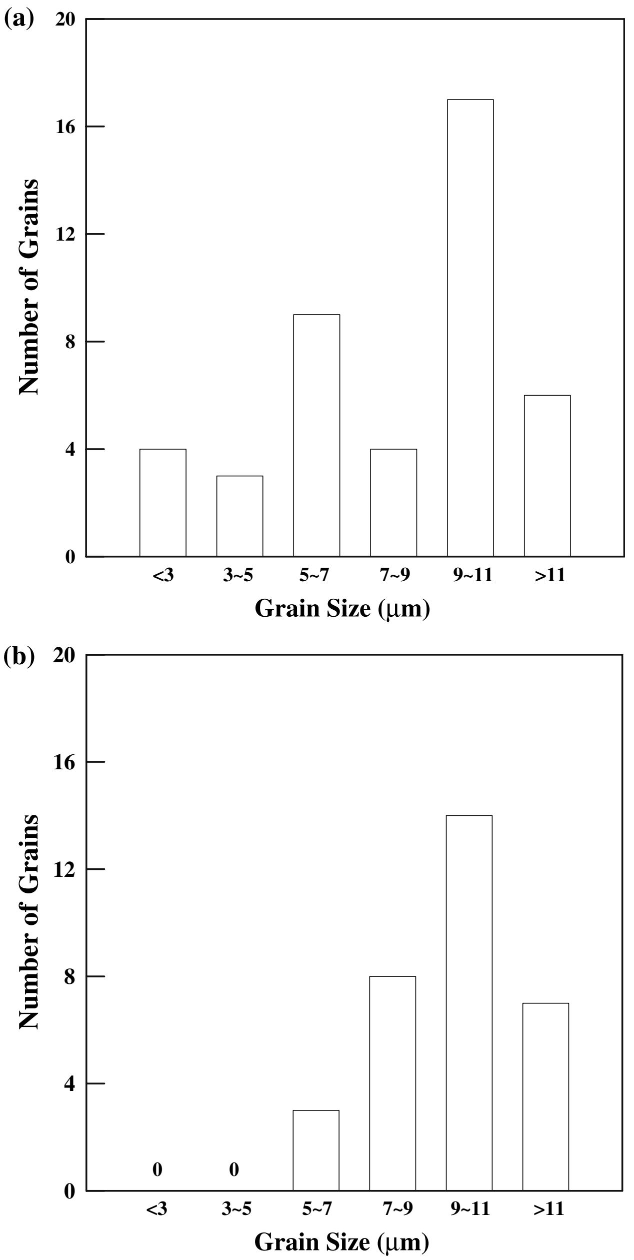

Fig. 12 The measure of grain size on the HAZ: (a) un-annealed wire and (b) 200 °C annealed wire

Conclusions

(1) The Recrystallization temperature of the unannealed wire was ~200 °C. The annealed wires (≥200 °C) contained fully annealed equiaxed grains with a few annealed twins. The tensile strength and the hardness had decreased, while the elongation had increased significantly.

(2) The grain size of the HAZ by the EFO process had a more centralized distribution when the annealing temperature was above 200 °C. The strength of the HAZ had a tendency to increase with increasing the annealing temperature, and the fully recrystallized wires possessed higher reliability.

(3) Tensile breakage sites of the EFO wires were in the HAZs. The nuclei of column-like grains in the Cu ball existed in the HAZ and the preferred orientation of the isotropy column-like grains was <100>.

Acknowledgement The authors are grateful to the Chinese National Science Council for its financial support (Contract: NSC 94-2216-E-006-008).

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