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Effect of Cold Rolling on Bending and Tensile Behavior of 7075 Aluminum Alloy

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Abstract: The present study reports the effect of cold working on bending and tensile behavior of 7075 Al alloy. A series of experiments involving cold rolling (58% cold work) have been conducted for the 7075-O aluminum alloy. It has been shown that cold rolling has a significant effect on increasing the yield strength and decreasing ductility of alloy. The variation in alloy ductility was found to correlate well with the fractography results of the tensile and bending tested specimens. The SEM fractographs of fractured surfaces for cold rolled specimens can be show very clearly the ductile to brittle transition behavior (absence of dimples) in bending test. It has been shown that, 7075-O aluminum alloy before cold rolling exhibits excellent bend properties so that, it is capable of being bent cold around a pin under high angle without crack or fracture, due to ductile behavior. Also, it can be seen that surface quality of starting materials is better than of cold rolled samples.

Key words: Bending test, tensile test, cold rolling, fractography, 7075 aluminum alloy

INTRODUCTION

The 7xxx series aluminum alloys have been widely used as structural materials due to their attractive comprehensive properties, such as low density, high strength, ductility, toughness and resistance to fatigue (Li *et al*., 2008; Heinz *et al*., 2000; Williams and Strake, 2003). The 7075 aluminum alloy is one of the most important engineering alloys and has been utilized extensively in aircraft structures because of its high strength-to-density ratio (Woei-Shyan *et al*., 2000).

The size and crystallographic alignment during cold working affects the properties of the material (Humphreys and Hatherly, 2004). The mechanical properties depend primarily on the number of dislocations introduced during cold working. As the dislocation density increases from ~10^{11} m^{-2} (typical of the annealed state) to ~10^{16} m^{-2} (typical of heavily deformed metals), the yield strength is increased by up to 5-6 times and the ductility decreased (Humphreys, 1997).

The bending test is a method for measuring the ductility of materials. Since bending is the most common type of deformation and occurs in almost all forming operations, the bending test is necessary for measuring sheet metal formability.

A little work has been reported on precipitation-strengthening Al-Zn-Mg 7000 series alloys, which are widely used for high strength structural applications such as aircrafts and sporting goods (Zhao *et al*., 2004).

The present study concentrates on the effects of cold rolling on bending and tensile behavior of 7075 Al alloy that frequently used in the automotive and aerospace industry.

MATERIALS AND METHODS

Research material: Experiments were conducted in Department of Mechanical Engineering. University of Malaya in 2008-2009. The chemical composition of the research material (7075 aluminum alloy) supplied by Alcoa, USA, in Table 1. The 7075 aluminum alloy plate, in O temper condition, have practical and industrial interest due to their higher formability in comparison to the other temper conditions. Thus, it was chosen as the Starting Material (SM).

Cold rolling: Cold rolling was carried out at room temperature by use of a LAB MILL by rolling plate from thickness 5 to 2.1 mm equal to 58% CW.

Table 1: Chemical composition (WT %) of the investigated alloy

Alloy	Values
Zn	5.60
Mg	2.50
Cu	1.60
Mn	0.30
Fe	0.50
Si	0.40
Cr	0.23
Ti	0.20
Others, total	0.15
Al	Balance

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Metallographic practice: Metallographic samples were prepared by sectioning the Al alloy plate by use of cut-off wheel machine so as to carry out metallography on the rolling plane. The metallographic specimens were prepared by mounting and grinding followed by polishing by use of alumina powder. The polished metallographic specimens were anodized by using Barker's reagent (5 mL HBF_4 48%) in 200 mL water at 30 V d-c for 2.5 min by using stainless steel cathode) according to ASTM standards (E 407) for grain structure under polarized light.

Mechanical testing

Hardness test: Hardness measurements were made to monitor the cold working response. Hardness measurements were made along the mid-thickness of polished sections cut along the rolling direction. Measurements were made using a vickers machine with a 10 kg load (Kalkanli and Yılmaz, 2008). Five measurements were made for each specimen.

Tensile properties: Tensile tests were conducted to evaluate the strength and ductility of the 7075-0 Al alloys. The tensile specimens were machined according to ASTM standards (B-557 M) sub-size specifications parallel to the rolling direction with gauge length of 25 mm. The tensile tests were performed at room temperature using Instron 4469 universal testing machine (Li *et al*., 2008). Three specimens for each heat treatment were operated at a constant crosshead speed 1 mm min^{-1}.

Bending test: Three point bend test specimens were made in accordance with test method (E 290) ASTM standards as shown in Fig. 1. The flat bending specimens for starting materials were machined with dimension 160×20×5 mm and for cold rolled samples, material prepared parallel to the rolling direction with dimension 160×20×2.1 mm which was associated with 58% CW.

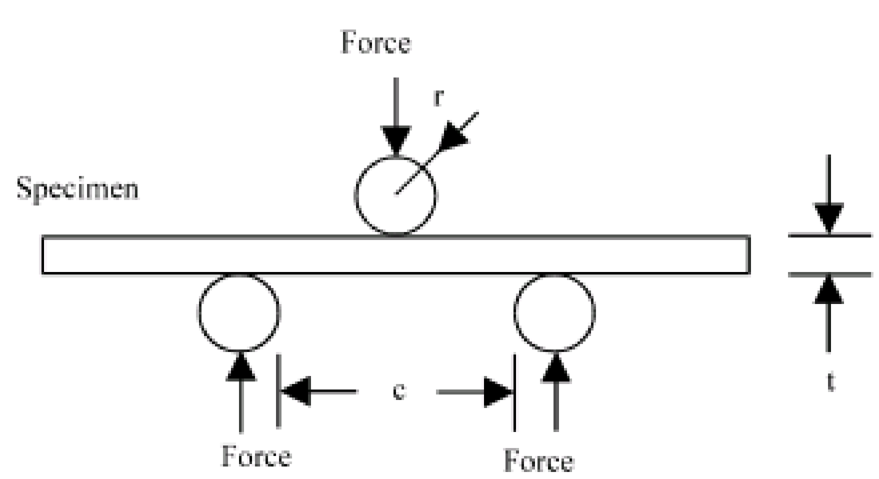

Fig. 1: Schematic fixture for the Guided-Bend test

The flexural stress formula is given by Eq. 1:

$$\sigma = M*Y/ I \tag{1}$$

where, σ is the flexural stress, M is the bending moment, Y is the distance from the natural axis and I is the moment of inertia. The maximum flexural surface stress occurs in the mid-point of the specimen. Therefore, the flexural stress can be expressed in terms of M, Y and I as follows:

$$M = P * L/4;\ Y = t/2;\ I = b * t^3/12 \tag{2}$$

$$\sigma = (3 * P * L)/ (2 * b * t^2) \tag{3}$$

where, P is the load applied by the test machine, t is the thickness of the specimen, b is the width of the specimen and L is the span length, respectively (Kalkanli and Yılmaz, 2008).

The bending test was conducted by using Instron universal testing machine. In bend tests sheet and plate being bent cold through an angle of 180° around a pin having a diameter equal to N times the thickness of the sheet or plate without cracking, the value of N for plate Al 7075 with thickness 2.1 mm is equal to 3. Specimens for all conditions were tested at ambient temperature with a strain rate of (1 mm min^{-1}). In three-point bend tests, the stress and strain at yield were determined.

The C value for cold rolled material was computed to be 17 mm as follows (Fig. 1):

$$C = 2r + 3t \pm t/2 \tag{4}$$

where, r is 5 mm (radius of the end of the mandrel or plunger) and t = 2.1 mm (sheet specimen thickness) and for starting material with thickness 5 mm, C value was computed to be 28 mm.

RESULTS AND DISCUSSION

Effect of cold rolling on microstructure: The microstructures of starting material, cold-rolled samples, for the 7075-O aluminum alloy are shown in Fig. 2a and b. These figures indicated that after cold rolling, the aspect ratio of the aluminum grains for 58% CW is equal to 35 at consistent with the macroscopic level of cold reduction has been increased. The cold work has the following two effects on the material:

- There is an increase in the stored energy of the material due to the high dislocation density and this provides the driving pressure for the Al recrystallization upon annealing

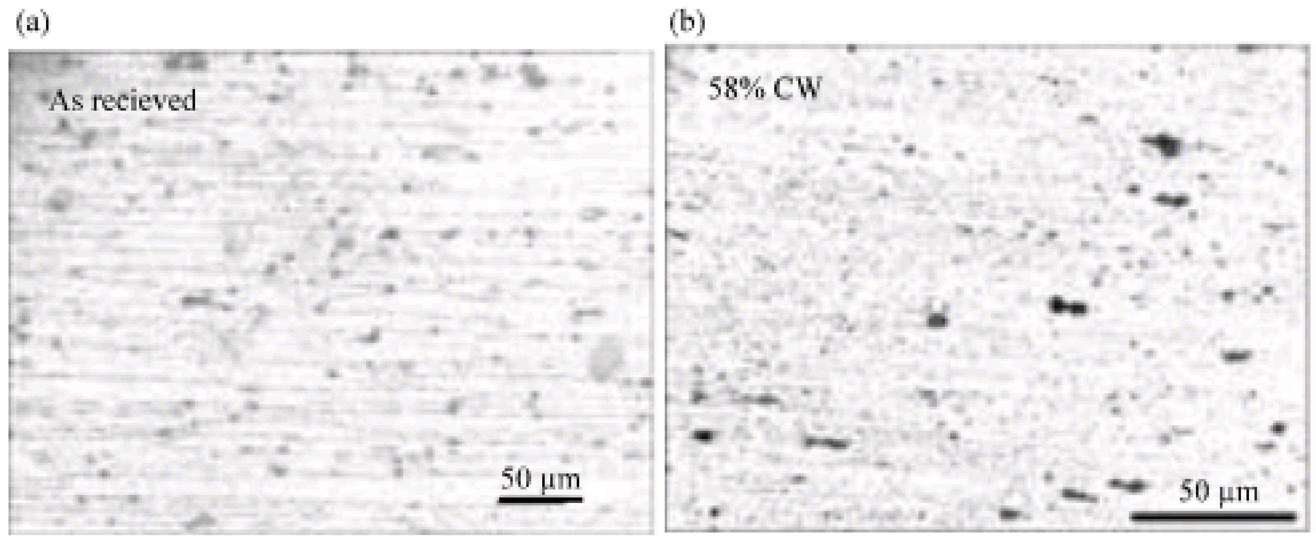

Fig. 2: Microstructures of 7075-O Al alloy, (a) starting material and (b) and 58% CW

Table 2: Tensile properties of 7075-O aluminum alloy

Specimen No.	Condition	Hardness vickers (HV)	Ultimate tensile strength (UTS) (Mpa)	0.2% Proof stress (MPa)	Elongation (%)
T-0	Starting material	70	234	125	15.5
T-1	58% CW	105	321	274	9.3

- The total Al grain boundary area is increased (Humphreys and Hatherly, 2004)

Effect of cold rolling on mechanical properties

Effect of cold work on tensile properties: The results of hardness and tensile properties of 7075 Al alloy at 58% of thickness reductions are shown in Table 2. It is observed that the tensile strength has increased from 234 to 321 MPa equal to 37.1% and elongation drop from 15.5 to 9.3% equal to 40% after 58% CW. Also, it is found that for 58% CW, there is a rapid increase in yield strength from 125 to 274 MPa equal to 119.25% because of many complicated array of different kinds of defects and the high density of dislocations produced in alloy and stored energy is associated with the large numbers of dislocations and other defects which are generated in the alloy during deformation. It is suggested that amount of dislocation density are the main responsible for variation in mechanical properties such as 0.2% proof stress, ultimate tensile strength, ductility and hardness during cold rolling. It is evident that with increasing density of dislocation, ductility decreasing because of dislocation movement remains low. The Taylor equation is used to explain the influence of dislocation density on the yield strength (σ_y) of alloys:

$$\sigma_y = \sigma_0 + \alpha M^T G b \rho^{1/2} + 0.85 M^T G b \ln(x/b)/2\pi\,(l\text{-}x) \quad (5)$$

where, σ_0, α, G, b, M^T, ρ, x and l are the friction stress, a constant, shear modulus, Burgers vector, Taylor factor, dislocation density, average size of precipitates and intermetallic spacing, respectively.

Table 3: Bending properties of 7075-O Al alloy

Specimen No.	Condition	Displacement at yield (mm)	Strain at yield (mm mm^{-1})	Stress at yield (MPa)
B0	Starting material	8.219	0.327	353.572
B1	58% CW	2.691	0.126	399.279

It is evident from Eq. 5, that yield stress of the materials is directly proportional to the dislocation density (Panigrahi and Jayaganthan, 2008; Kassner, 2004).

In addition, cold rolling produces an increase in hardness from 70 HV for as received material to 105 HV for 58% CW. It is due to the resistance to plastic deformation.

Observation of fracture surfaces of specimens fractured at room temperature in tensile condition show dimples; which indicate the typical micro-void coalescence (MVC) mechanism of ductile failure are shown in Fig. 3a and b.

Effect of cold work on bending properties: The results of bending properties of 7075-O Al alloy both starting material and 58% CW are shown in Table 3. It is observed that the displacement at yield has decreased from 8.219 to 2.691 mm equal to 67.2% and stress at yield has increased from 353.572 to 399.279 MPa after 58% CW. This is because many complicated array of different kinds of defects are generated in alloy during deformation.

The SEM fractographs for cold rolled specimen ruptured in bending test are shown in Fig. 4a-c; that show clearly brittle failure due to present of some quasi-cleavage regions and absence of dimples. On the other hand, the photographs of starting material and 58% cold rolled 7075-O Al alloy are shown in Fig. 5.

In this study, effect of cold rolling on fracture behavior in bending test is explained. In general, the main difference between brittle and ductile fracture can be attributed to the amount of plastic deformation that the material undergoes before fracture occurs. Ductile materials demonstrate large amounts of plastic deformation while brittle materials show little or no plastic deformation before fracture. The cold rolling has resulted in increase in yield stress and has caused a lack of plastic

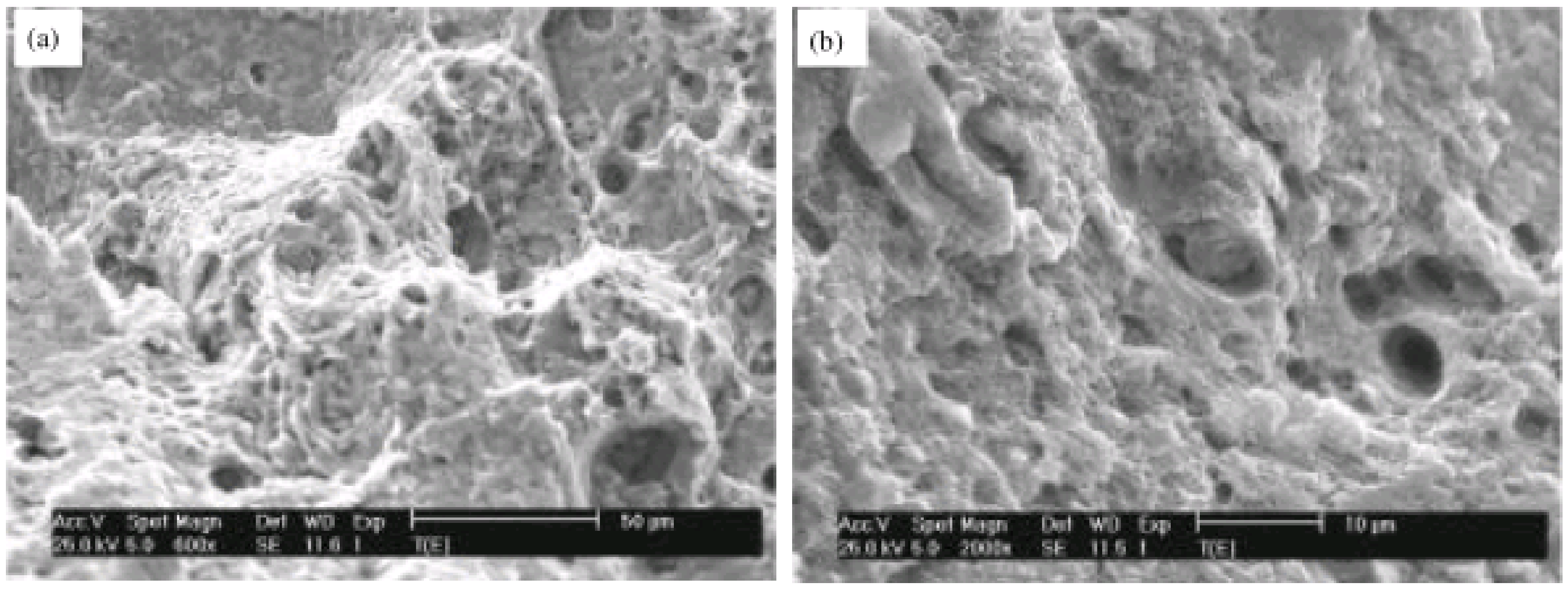

Fig. 3: SEM photographs of fracture surfaces of 7075-O aluminum alloy, starting material, in tensile test showing: (a) overall morphology; (b) high magnification of (a) that shows the ductile dimples are prominent

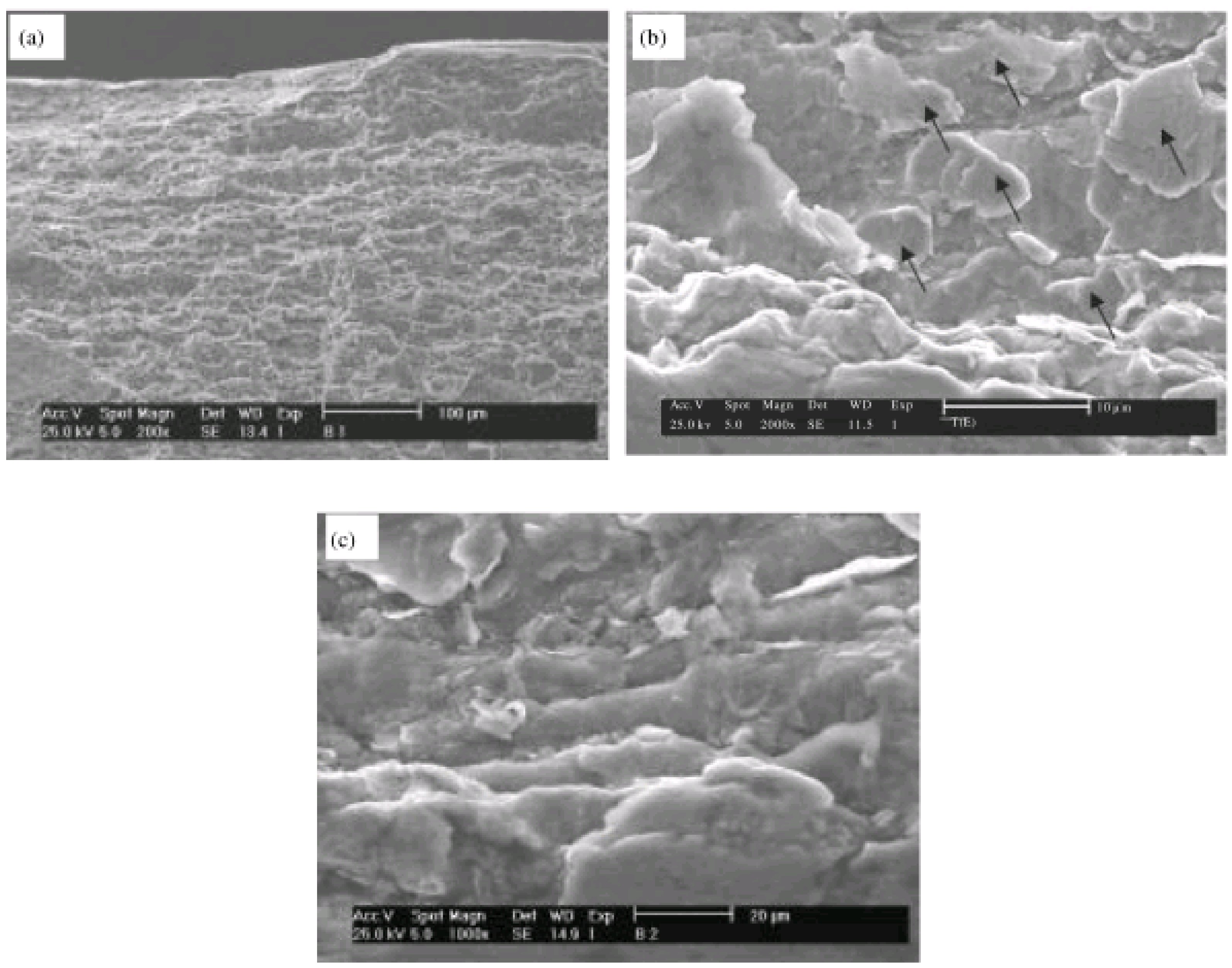

Fig. 4: SEM photographs of fracture surfaces of 7075-O aluminum alloy for 58% CW, in bending test showing: (a) overall morphology, (b-c) higher magnification of (a) including cleavage-like features (arrows in b), indicating brittle failure mode

deformation; which has also resulted in brittle fracture mechanism. Also, the long grain boundaries in rolled metal can accommodate suitable sites for crack initiation and preferential direction for crack growth or crack propagation along the long grain boundaries.

Thornton and Colangelo (1985) have also reported that brittle fractures are frequently associated with cracks or other flaws in the material and in contrast to ductile behavior, they are characterized by low energy absorption and a lack of gross plastic deformation.

The stress required to move a dislocation depends on the obstacles such as solute atoms and grain boundaries. If the stress to move dislocation too high, the metal will fail instead by the propagation of cracks that is the failure

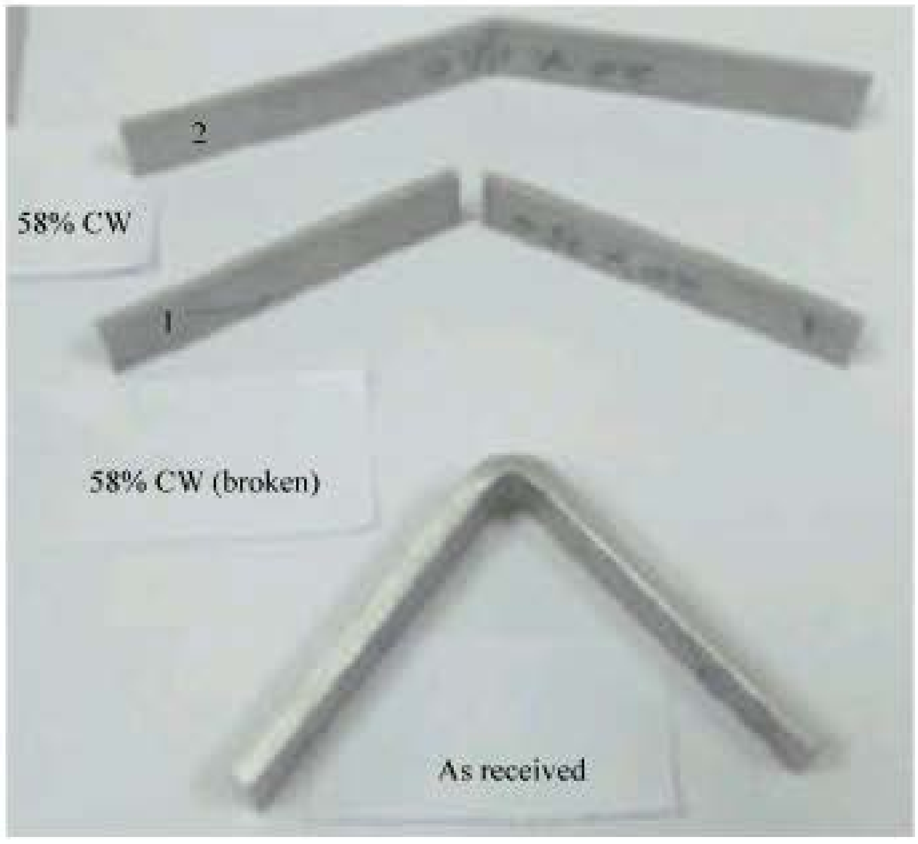

Fig. 5: Macroscopic photographs of starting material and cold rolled samples of 7075-O Al alloy

will be brittle. Jayatilaka (1979) has reported that the dislocations at the head of a pile-up may coalesce, to nucleate a crack.

The fracture surfaces of the 7075-O Al alloy fractured in tensile tests at room temperature were examined to correlate the fracture characteristics with properties. The high ductility and low yield stress in starting material are corresponding to ductile fracture. Ductile to brittle behavior of cold rolled samples can be very clearly seen (specimen has broken under bending), whilst starting materials show a ductile behavior (specimen has bended under high angle). It is suggested (Chen and Wang, 1994) that the main factor promoting the transition from the fibrous crack to cleavage is the increase of the local tensile stress ahead of the crack which is caused by the increase of the triaxiality of stress and the apparent normal stress in the remaining ligament. The orientation of the sheet in relation to the rolling direction can be important in the bending operation. Because, during rolling inclusions and other defects become elongated in the rolling direction. When subjected to a bending test, these elongated defects lower the resistance to fracture. Furthermore, the photographs are shown in Fig. 5 indicated the difference in surface qualities. It can be seen that surface quality of starting materials is better than of cold rolled samples. The results of bending test are in agreement with tensile properties.

CONCLUSION

The aim of this study was to study the fractography of the 7075 aluminum alloy deformed by cold rolling. It was shown that the variation in alloy ductility and strength was to correlate well with the fractography results of both the tensile and bending tested specimens. Profound effects of cold working on bending and tensile behavior of 7075-O Al alloy have been observed. It is found that after 58% CW, there is a rapid increase in yield strength equal to 119.25% due to high density of dislocations. Also, there is an increase in the tensile strength (UTS) and hardness and decrease in percentage elongation of the rolled material. It also has been shown that there is a decrease in displacement and strain at yield and an increase in yield stress for 58% CW in bending test; this material behavior was justified due to high density of dislocations in the cold rolled sample. Furthermore, it has been shown that starting material is capable of being bent cold around a pin under high angle without crack or fracture, due to ductile behavior. Whilst, cold rolled samples produced crack and broke at low bending angle. The SEM fractographs for the cold-worked sample showed a fracture surface including some quasi-cleavage regions and absence of dimples reflecting to brittle fracture mechanism.

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