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Influence of Cold Rolling and Annealing on the Tensile Properties of Aluminum 7075 Alloy

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Abstract

The present work reports the effect of cold rolling and subsequent annealing at different temperatures on the tensile behavior of 7075 aluminum alloy. The cold rolling has been carried out in between 12-28% and was annealed at various temperatures in the range of 225-325 ^{o}C for 5 min. Hardness test and tensile tests were carried out to evaluate tensile and ductility parameters. All the tensile specimens were taken from the transverse direction of the cold rolled and annealed sample. It has been observed that the cold rolling has a significant effect on the increase in the yield strength and lowering the ductility of the alloy. It was also observed that the cold rolled samples, annealed at 275^{o}C showed lower total elongation in the transverse direction, while for samples annealed at high temperatures the total elongation values were observed to be high. In general it is also observed that formability (UTS/σ_y) of cold worked and annealed samples were high when compared to cold worked samples. Fractographic study using SEM analysis was carried out for all the conditions. Failure took place by formation of dimples indicating ductile fracture

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*Keywords:*Cold rolling; annealing; strength and ductility parameters.

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Nomenclature

Cw	Cold worked
e	Engineering strain
ε	True strain
K	Strength coefficient
n	Stain hardening exponent
Rex	Recrystallization
S	Engineering stress
UTS	Ultimate tensile strength
σ_y/YS	Yield strength
σ	True strength

1. Introduction

The 7xxx series Aluminium alloys have been widely used as structural material due to their attractive widespread properties such as low density, high strength, ductility, toughness and resistance to fatigue [L. I. Jin-Feng et al 2008 ; Heinz et al 2000; Williams JC 2003]. The 7075 Aluminium alloy is one of the most important engineering alloy. It has been utilized extensively in aircraft construction due to high strength to density ratio. Size and crystallographic orientation of grains in the process of cold deformation affect the properties of material [F.J.Humphreys and .Hatherly 2004]. The mechanical behaviour depends primarily on the number and distribution of dislocations introduced due to cold deformation. When the dislocation density increases from 10^{11} m^{-2}, a value typical for annealing state to about 10^{16} m^{-2} for considerably deformed metal, the yield strength increase by a factor of 5-6 and the ductility decreased [F.J.Humphreys 1997].

In addition, good ductility is also required for formability. However, the enhancement of the strength of the material maintaining reasonable ductility is a permanent challenge. The known method is to increase ductility is through recrystallization done by annealing process. By recrystallization, there is a gradual decrease in the tensile strength (UTS), yield strength (YS) and hardness, and increases the elongation of the rolled material. The formability of the sheet metal is an important parameter of the manufacturing process design [Lee NS et al 2009].
Tajally et al [M. Tajally et al 2010] studied the effect of cold rolling and annealing temperature on the fracture behavior as well as tensile behavior of 7075 Al alloy and observed that, there is increase in yield strength due to high dislocation density. It was found that remarkable increase in % elongation was observed when the specimens were recrystallized at temperature above 265°C and also reported that yield and tensile strength gradually decreased at the same condition. The observation made when the tensile samples were taken parallel to the rolling direction.
Tajally et al [M.Tajally et al 2011] studied on the mechanical and anisotropic behaviour of 7075 Al alloy sheet and stated that cold rolled sample and subsequent annealing at 270°C resulted lower elongation in the transverse direction. However, the samples annealed at higher temperature the elongation values were high. They have also observed that cold rolling and subsequent annealing refine the grain size and grain length resulting in greater ductility in the transverse direction which attributed to improvement of formability. Whereas longer grains in the cold worked sample restrict the plastic deformation. This behaviour is indicated by the lower elongation in the cold worked condition.

Strain–hardening is an important strengthening process for metals. The strain–hardening exponent is one of the most important indicators of the strain–hardening properties of metallic materials [T.Xu et al 2012]. The strength, ductility, toughness, and deformability of materials are intimately related to their strain–hardening characteristics. Strain hardening exponent as a parameter can be used to measure the strain–hardening capacity in the uniform plastic deformation stage during the tensile process, as it not only dominates the punch-forming properties of materials but is also indicative of the ability of the material to retard the localization of deformation.

Present work has been aimed to study the effect of cold rolling and annealing temperature on the tensile behavior of aluminium alloy 7075 which was received in T651 condition (solution heat treated, stress relived by stretching and artificial aged) and to evaluate its strength and ductility parameters. This study has a great importance related to the automobile and aerospace industries.

2. Experimental procedure

The chemical composition of 7075 Al alloy is given in table 1. The initial condition of the material was in peak aged condition that is in T651, with the thickness of 6.35 mm. The T651 plate, in the as received form was too hard to be cold worked. Hence the material was full annealed [M. Tajally et al 2010].

Table 1. Chemical composition (w%) of 7075-T6 Aluminum alloy

Zn	Mg	Cu	Fe	Si	Cr	Mn	Ti	other	Al
5.5	2.4	1.3	0.16	0.05	0.223	0.035	0.071	0.15	Bal

Annealing was carried out at 415 ^oC for 150 min followed by furnace cooling to reduce hardness from 177 Hv to 68 Hv. This is to bring the peak aged temper condition to O – temper condition. The 7075 Al alloy plate in O-temper condition was chosen as the starting material(SM). The O- tempered 7075 Al alloy found to have industrial application due to their higher formability in comparison to the other temper conditions.

Cold rolling was carried out at room temperature by using of lab mill by rolling plate with varying thickness. The thickness was reduced from 6.35mm to 5.5mm (12%), 5mm (19%) and 4.4 mm (28%) reductions. The cold rolled samples were annealed at various tempers in the range of 225 – 325 ^oC for 5 min in a muffle furnace. Finally the hot annealed samples were air cooled to the room temperature. The schematic representation of the treatment followed, shown in the figure 1.

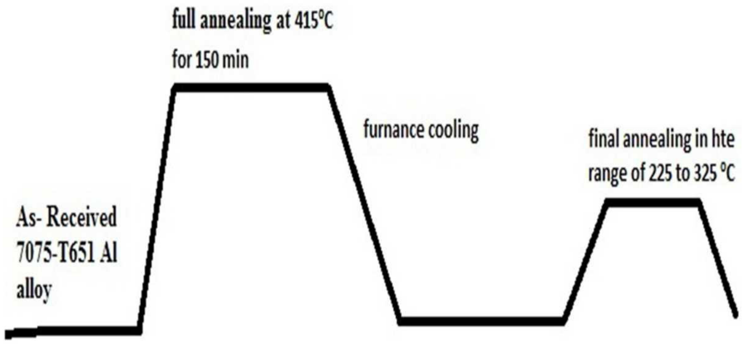


Figure1. Schematic representation of the heat treatment cycle followed

Metallographic samples were prepared for all the conditions. The specimens were mounted and grounded on the various grit papers followed by disc polishing by using 1 micrometer diamond paste. In order to reveal the microstructure all the samples were etched with keller's reagent.

Tensile samples were cut along the transverse direction of the plate to evaluate tensile properties of all the treated samples. The tensile specimens were machined according to ASTM E8 sub size standard and the tension test was carried at room temperature. The dimensions of the tension sample were taken as 20 mm X 6 mm X 4 m with gauge length of 20 mm. The test was conducted on the SAHIMADZU universal testing machine, at cross head speed of 2 mm / min.

Strength and ductility parameters were calculated from the tensile test. Initially engineering stress and engineering strain were calculated from the data of extension and load applied in the tension test. Then true stress and true strain were calculated from the equation 1 and 2.

$$\varepsilon = \ln (1+e) \qquad (1)$$

$$\sigma = s\,(1+e) \qquad (2)$$

Where s and e are engineering stress and strain respectively, ε and σ are true strain and strain. True stress-strain curve gives a true indication of deformation characteristics because it is based on the instantaneous dimension of the specimen. The true stress-strain curve is also known as the flow curve. The flow curve of many metals in the region of uniform plastic deformation can be expressed by the simple power law.

$$\sigma = K\,\varepsilon^{n} \qquad (3)$$

Where n is the strain hardening exponent K is the strength coefficient. Log-log plot of true stress-strain curve from yield point up to the maximum load will result in a straight line where n is the slope and K is the true stress at ε = 1.0.

Microhardness test was carried out on finely polished surface on all the samples. Hardness test was carried out on HVS-20 SHIMADZU micro hardness machine with a load of 10 Kgf for 15 sec. Fracture surface of the broken specimens from the tensile test of various cold worked samples were taken for the fractographic study using scanning electron microscope (SEM).

3. Results and discussions

3.1. Microstructure

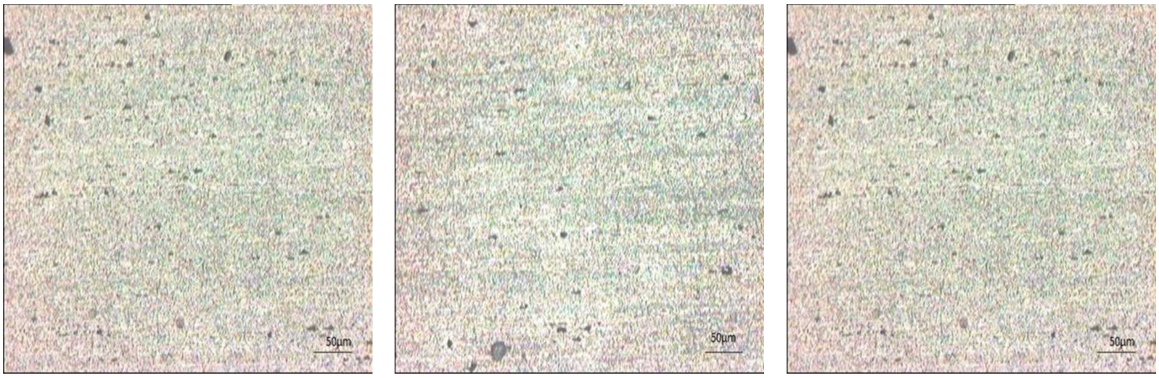
The microstructures of cold rolled and cold rolled followed by annealing samples of the Al 7075 alloy are shown in figure 2. It has been observed that after cold rolling, the accept ratio of the Aluminium grains were increased and is consistent with the macroscopic level of cold reductions.

3.2. Tensile test

Figure 3 shows the graphical representation of evaluating strength and ductility parameters in 28% reduction and subsequent annealed at 325°C. Similarly for other samples tensile and ductility parameters were evaluated and consolidated in table 2.

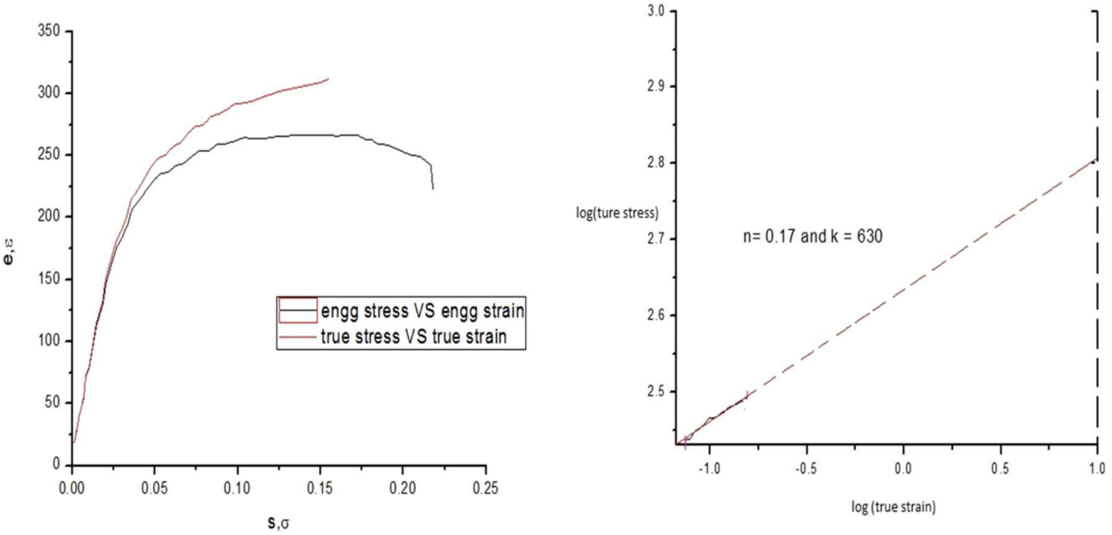
The various strength and ductility parameters of the 7075-O tempered alloy in the cold rolled and subsequent annealed condition are recorded in table 2. Also the hardness values of the material in the respective condition are included in the table 2. The column charts in figure 4 (a) and (b) represent the tensile properties of the cold rolled and starting material(SM). It has been observed that as the degree of cold work increases the value of UTS and YS increased where as the % elongation decreased. Also, figure 5 shows the strain hardening exponent of the cold rolled samples and for starting material.

The main aim of the present work is to study the influence of the cold rolling and subsequent annealing temperature on the tensile behaviour. The variation of the proof stress, UTS and hardness are shown in figure 6. It may be seen that the proof stress and UTS are highest for sample which is cold rolled for 28% and annealed for 225 °C / 5 min. It is also observed that the hardness depend on the amount of the cold reduction and annealing temperature. This can be seen from the figure 5 and 7.



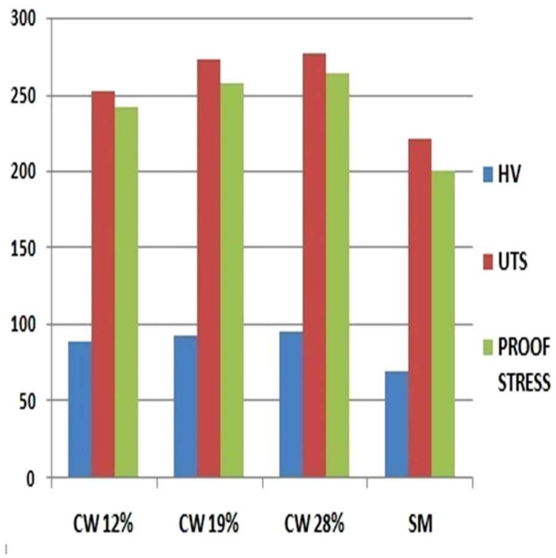
(a) (b) (c)

Figure 2.Microstructures (a) full annealed condition i.e., annealed at 450 ºC for 150 min. (b) 19 % cold (c) 19 % cold rolled and subsequent annealed at 275 ºC.

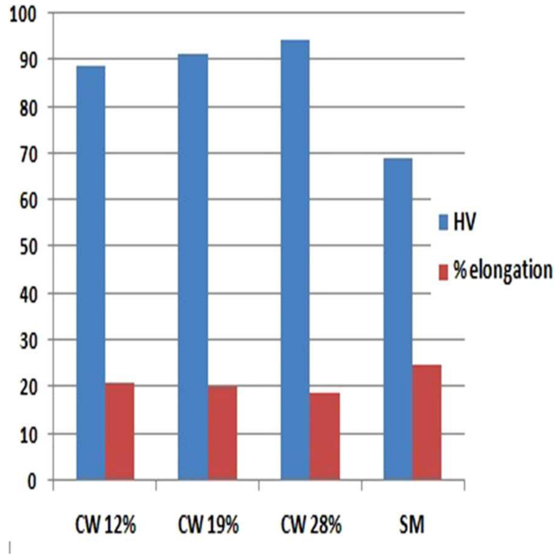


(a) (b)

Figure 3. Evaluation of strength and ductility parameters of the sample Tmt3 -C3-1L that is cold reduction up to 28% reduction and annealed at 325ºC (a) Engineering stress- stress and True stress- strain diagram (b) Log – Log plot of true stress – strain, slop of it gives n where as K true stress at ε= 1.0



(a)



(b)

Figure 4. Effect of cold work on the (a) Hardness, tensile strength, proof stress and(b) elongation of the cold worked 7075 –O Al alloy

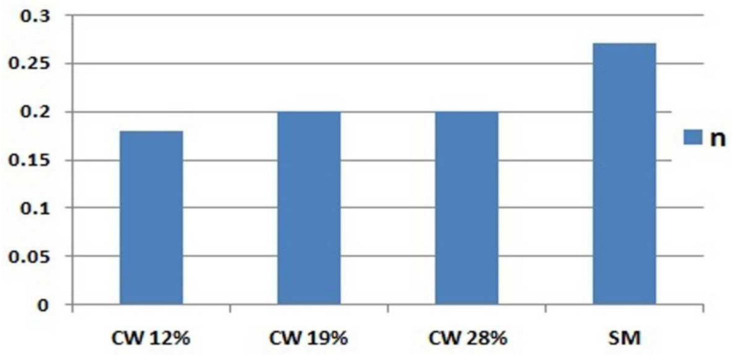


Figure 5. Strain hardening exponent of the cold rolled samples and for starting material.

It has been observed from table 2 and figure 7, that cold-rolled sample and annealed at 275^{o}C showed lower total elongation; while the samples annealed at high temperatures the total elongation values were high. This can be explained in terms of the microstructure and mechanical properties. In the cold rolled sheet, the longer grains restrict the plastic deformation along the transverse direction, as indicated by the lower elongation. However, cold rolling and subsequent annealing refine the grain size, especially the grain length, resulting in a greater ductility in the transverse direction; consequently, the formability along this direction was also improved [M.Tajally et al 2011].

It has been also observed that the (UTS/σ_y) formability of the cold worked and annealed samples were increased compared to the cold worked samples.

Table 2. Tensile and ductility parameters of the 7075-O tempered alloy in the cold rolled and subsequent annealed condition.

Specimen no.	Condition	Hv	UTS (MPa)	YS (MPa)	UTS/σ_y	% TE	% RA	% UE	n	K (MPa)
SM	450 °C for 150 min	68	221	200	1.105	25.5	18.5	17	0.12	812
CW 12 %	12% CW	88.7	251.3	241.12	1.04	21	19.7	11	0.18	645.6
Tmt1-A1-1L	12% CW +ReX For 225 °C/5min	82.9	242.7	230	1.05	21.8	19.8	11.07	0.17	588
Tmt2-B1-1L	12% CW +ReX for 275 °C/5min	81.2	249.4	203.6	1.22	20.16	19.8	12.77	0.29	831.7
Tmt3-C1-1L	12% CW +ReX For 325 °C/5min	78.74	238.8	220.8	1.08	25.9	19.5	12.55	0.20	660.5
CW 19%	19 % CW	91.62	273.2	257.47	1.06	20.17	18.55	11.37	0.21	923
Tmt1-A2-1L	19% CW+ReX For 225 °C/5min	85.02	267	245	1.08	23	23.23	14.17	0.26	1000
Tmt2-B2-1L	19% CW +ReX For 275 °C/5min	83.52	249.2	204.2	1.22	21.49	19.58	14.85	0.24	851
Tmt3-S2-CL	19% CW +ReX For 325 °C/5min	80.7	252.1	230	1.09	22.7	19.7	14.05	0.22	758
CW 28%	28 % CW	94.32	276.4	263	1.05	19.3	21.33	10.1	0.21	892
Tmt1-A3-1L	28% CW +ReX For 225 °C/5min	88.4	269	255	1.09	22	23	11	0.22	800
Tmt2-B3-1L	28% CW+ReX for 275 °C/5min	84	268	203.9	1.31	19.2	20.13	12.83	0.3	1318
Tmt3 -C3-1L	28% CW +ReX For 325 °C/5min	83.32	266.4	255	1.04	21.8	19.7	12.3	0.17	630

Cw:- cold working ;Rex :- Recrystallization

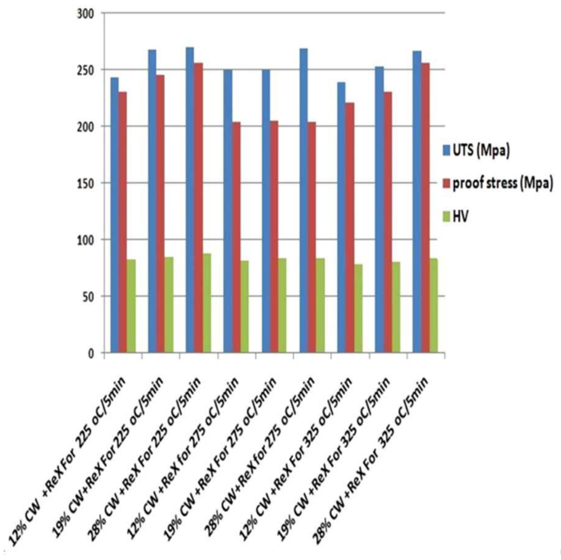


Figure 6.Variation of the proof stress, UTS and hardness of cold rolled and subsequent annealed sample

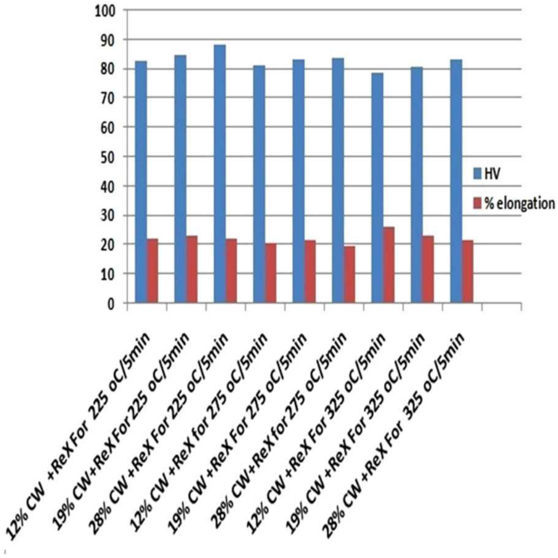


Figure 7. Effect of cold rolling on the total elongation and hardness

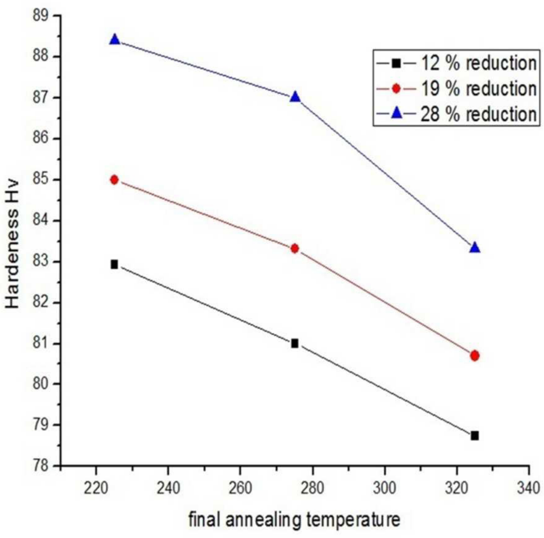


Figure 8. Micro hardness in correlation with the various annealing temperatures

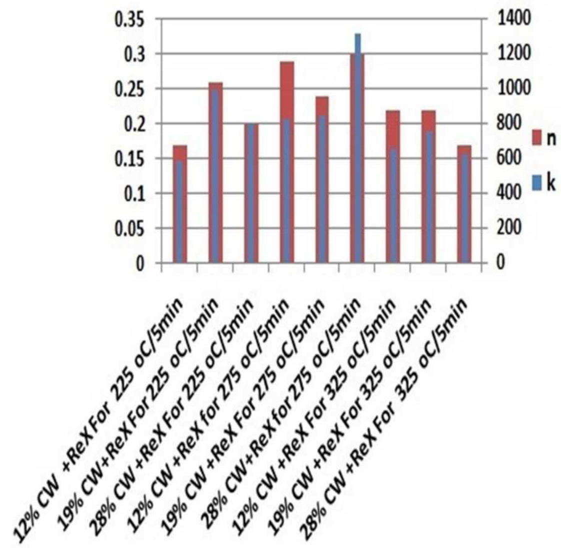


Figure 9. Variation of the n and K with cold rolling and subsequent annealing

The variation of the work hardening parameters namely the work hardening exponent (n) and the strength coefficient (K) with the cold rolling and subsequent annealing are shown in table 2 and figure 9 respectively. It is observed that the sample cold rolled to 19% and subsequent annealed at 325 ^{o}C reported high strength coefficient of 1313 Mpa.

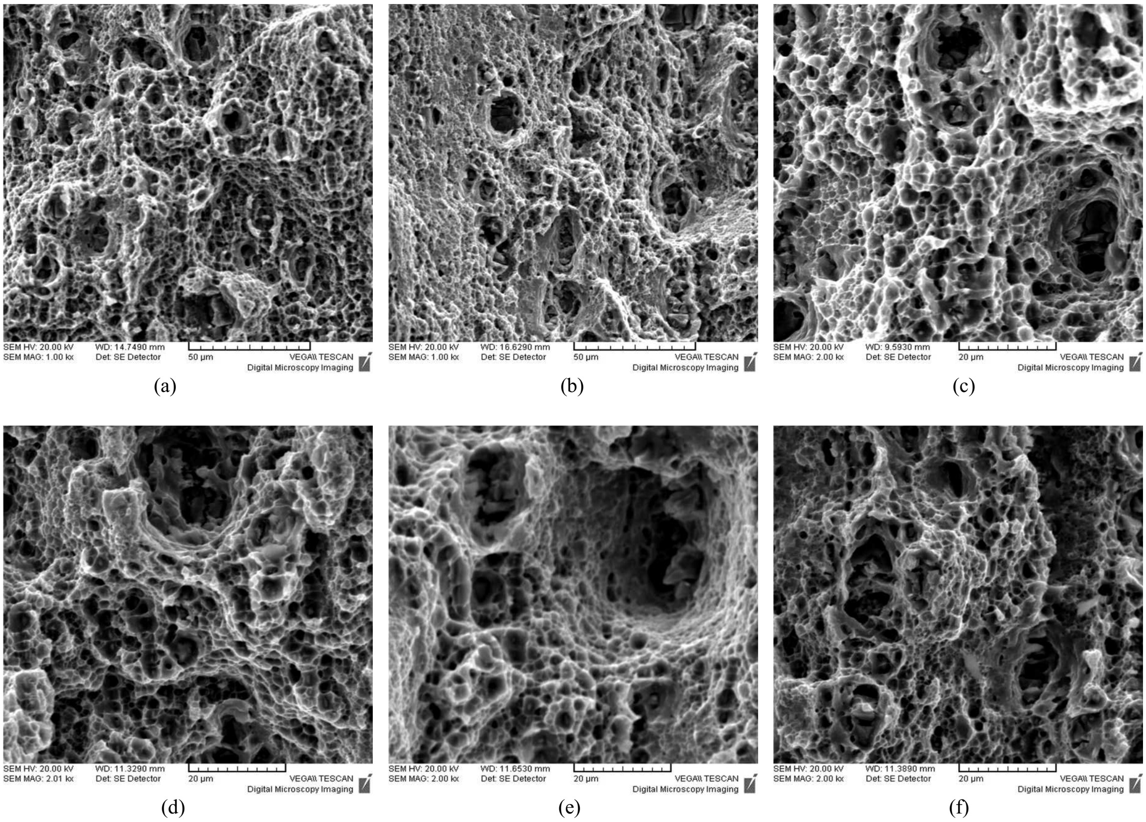
The effect of cold rolling and annealing at recrystallization temperatures of 225 °C, 275 °C and 325 °C on the hardness and tensile behaviour are shown in table 2, figure 5 and 7 respectively. There is a gradual decrease in the tensile strength (UTS), yield strength (YS), hardness and continuous increase in elongation of the rolled material with increase of annealing temperatures. The decrease in UTS, YS and hardness on recrystallization is obviously due to decrease in density level of dislocation resulting from recrystallization. An exception was observed when cold rolled sample annealed at 275°C. This behaviour has been explained by Tajally [M. Tajally et al 2010].

The Taylor equation is used to explain the influence of dislocation density on the yield strength (σ_y) of alloys [Panigrahi SK 2008 ; Kassner 2004].

$$\sigma_y = \sigma_0 + \alpha M^T Gb\rho^{1/2} + 0.85\, M^T\, Gb \ln (x/b)/ 2\pi(l-x) \qquad (4)$$

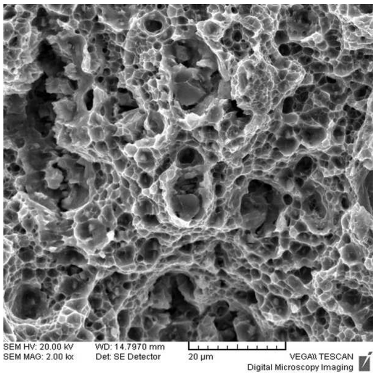
Where σ_0, α, G, b, M^T, ρ, x and l are friction stress, a constant, shear modulus, Burgers vector, Taylor factor, dislocation density, average size of precipitates and the inter-particle spacing respectively . It is evident from Eq. (4), that yield stress varies directly as the dislocation density of a material. This is why yield stress of the 7075 Al alloy falls due to decrease in dislocation density resulting from recrystallization.

Figure 10 shows the SEM fracture surface of the tensile samples which are 12% and 28% cold rolled respectively without any final annealing. The SEM micrograph indicates fine circular dimples. As compared to the 12% cold work, the finest dimples are observed in the 28% deformed sample. In cold rolled and subsequent annealed samples of 12 % and 28 % reductions the SEM micrographs indicates dimples. The size of the dimple depends on the degree of cold rolling and annealing temperatures. The fracture surface indicates the typical micro-void coalescence (MVC) mechanism of ductile failure.

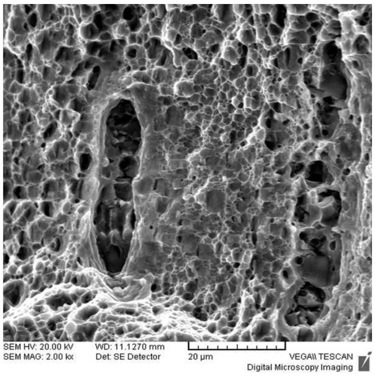


(a) (b) (c)

(d) (e) (f)



(g)



(h)

Figure 10. SEM images of fractured tensile samples at 2000 X (20 µm) (a)7075 O tempered and 12 % cold rolled (b) 7075 O tempered and 28 % cold rolled (c) Tmt1-A1-1L (d) Tmt2-B1-1L (e) Tmt3-C1-1L (f) Tmt1-A3-1L (g) Tmt2-B3-1L (h)Tmt3 -C3-1L

4. Conclusions

- Profound effect of cold rolling and annealing temperature on the tensile behaviour of 7075 Al alloy have been observed.
- Cold rolling and annealed at 275^{o}C shown lower elongation, while the sample annealed at higher temperature the elongation values were high.
- Formability of cold worked and annealed samples were increased compared to cold worked samples.
- Fracture behaviour in all the sample was observed to be ductile in nature.

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