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Cold Rolling Effect on Mechanical Properties and Fracture Toughness Behavior of AA1050 Aluminum Alloy

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Keywords：AA1050 Aluminum Alloy, mechanical properties, fracture toughness behavior.

ABSTRACT

The present paper reveals an experimental investigation of the effect of cold rolling (CR) on the mechanical properties and fracture toughness behavior of AA1050 H16 aluminum alloy. The received materials were cold rolled at different percentage of cold rolling (25%, 50% and 75%). The mechanical tensile properties of the specimens with different cold rolling percentage were determined by monotonic tensile test along two directions (RD: rolling direction, TD: transversal direction). Besides, the fracture toughness behavior of the cold rolled and as received alloy was evaluated by fracture toughness test using central cracked panels (CCP) specimens along two direction (RD and TD). ASTME1820 standard was used to evaluate the fracture toughness parameter $J_{0.2}$ and J-Δa curves. Experimental results found that the cold rolling has profound effect on resistance anisotropy which improves with the amount of %CR. The highest strength and fracture toughness were shown in the longitudinal direction in the studies alloy. In addition, cold rolling has been found to have an important effect on the decrease in fracture toughness parameter of the alloy which increases with the amount of %CR. The examination of the fracture surfaces with the scanning electron microscope (SEM) shown dimpled morphology for the ductile fracture mechanism in the received material and quasi-cleavage areas in cold-rolled specimens, corresponding to ductile to brittle fracture mechanism.

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INTRODUCTION

The 1XXX series aluminum (non-heat-treatable alloys) are employed in a huge diversity industrial domain (construction, chemical, electrical, vessels, food, cables...) due to good their attractive properties, such a high corrosion resistance, excellent workability and low density and strength (Rangaraju et al., 2005; George et al., 2015; Wang et al., 2017; Allazadeh, 2018 and Ramaswamya et al., 2012). The commercially pure aluminium AA1050H16 is one of the more important aluminium alloys is used for sheet metal forming because of its high ductility and good workability and formability (Zhao et al., 2013).

During the sheet forming operation, AA1050 is subjected to high irreversible deformation. This plastic deformation created in the alloy after cold rolling can modify the mechanical and fracture toughness behaviour (Aigbodion et al., 2015; Gupta et al., 2016; Ortiz et al., 2007 and Tajally et al., 2007). The fracture is the principal property to estimate the fracture resistance to damage of materials (Mrówka-Nowotnik et al., 2009 and Frómeta et al.2020). Many studies prove that the plastic deformation leads to increase the tensile strength and hardness and decrease the ductility rapidly. Moreover, divers investigations have been evaluated the effect of cold rolling on fracture toughness parameters of several steels alloys however a little studies concerning the aluminium alloys. The investigation performed on various steels alloys show that the high effect of the cold rolling on the fracture toughness parameters (Hagiwara et al., 2001; Madi et al., 2020 and Kim et al.2018). The cold rolling conducts to decrease the resistance to the initiation of cracking $J_{0.2}$.

In this research, the effect of cold rolling on mechanical and fracture toughness behaviour of AA1050H16 aluminium alloy was investigated. The sheets of AA1050H16 aluminium alloy were cold rolled at various reduction ration 25%, 50% and 75%. The tensile properties, hardness and fracture toughness parameters were studied and compared before and after cold rolling utilizing tensile test, microhardness measurement and fracture toughness test in two directions (RD: rolling direction and TD: transversal direction).

EXPERIMENTAL ANALYSIS

Materials and cold rolling procedure

In this work, the commercially pure aluminum AA1050H16 sheet of 3mm thickness has been chosen to study. The chemical composition of this material is nominated in Table 1. The plate of starting sheet of AA1050H16 was cold rolled at ambient temperature by the laboratory rolling mill. The thickness of plate specimens was lessened from 3 to 2.25, 1.5 and 0.75. The percentages of cold rolling reduction were 25%, 50% and 75%.

Table 1. Chemical composition of AA1050H16 (wt %).

Element	Al	Cu	Mg	Si	Fe	Mn	Zn	Ti
Content	Bal.	0.05	0.05	0.25	0.4	0.05	0.07	0.05

Tensile test

In this work, the study of the mechanical properties of the AA1050H16 aluminium alloy is carried out by the monotonic tensile test and the hardness test. The mechanical tensile properties of the starting and cold rolled AA1050H16 aluminium alloy sheet were evaluated along two directions (rolling RD and transverse TD) using monotonic tensile tests. The tensile test samples used in this study were machined according to NF EN 10002-1 standard shown in Fig1. The monotonic tensile test was performed using a 50kN LLOYD universal tensile machine at room temperature with at crosshead speed of 10 mm/min. the axial strain was evaluated automatically by an axial extensometer (length 25mm). Four samples were utilized for each test.

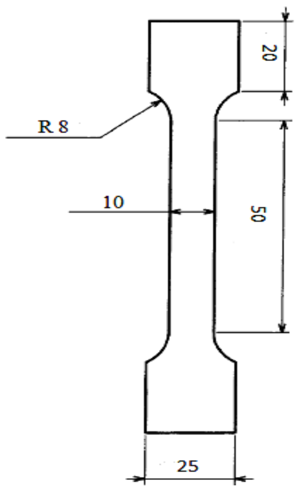


Fig. 1. Geometry of the tensile specimen (in mm)

Hardness test

Hardness was performed investing the micro Vickers machine through the use of a load of 50g and a loading time of 15s at ambient temperature. The micro hardness measurements were carried out for as-received and cold rolling alloy samples. Six measurements were effected for each sample.

Fracture toughness test

To study the fracture toughness behavior of AA1050H16 aluminum alloy before and after cold rolling, central cracked panels (CCP) specimens were used. The dimensions and geometry of CCP specimens were illustrated in Fig 2. This specimen was machined along both directions (rolling direction (RD) and transversal direction (TD)) using the wire cut machine. Then, they were pre-cracked by fatigue test to 5mm (a0/W=0.5) where a_0 is the half initial crack length and W is the half width of the specimen. ASTME1820 standard using the single sample technique was employed to evaluate the J-Δa curves and the fracture toughness parameter J0.2 (Imad et al., 2003).

The fracture toughness tests were performed by universal tensile machine 50kN LLOYD at room temperature under control displacement at a cross lead speed of 1mm/min and the load vs. displacement curves were registered.

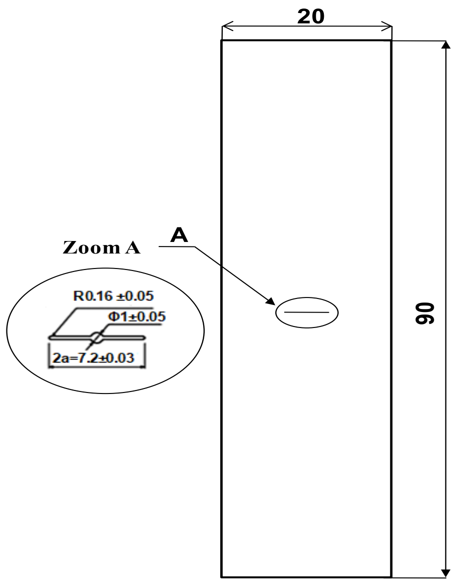


Fig. 2. CCP specimens dimensions and Geometry (in mm).

During the fracture toughness test, the values of load and displacement were saved at the same time in the computer. The J values were calculated as in equation (1) (Schwalbe et al., 1995):

$$J = \frac{K^2}{E} + \frac{U^*}{B(W-a_0)} \tag{1}$$

For the CCP specimen, the stress intensity factor K is obtained from the following Equation (2) (Lei et al1997):

$$K = \frac{P}{B\sqrt{2W}}\left[1 - 0.025\left(\frac{a}{w}\right)^2 + 0.06\left(\frac{a}{w}\right)^4\sqrt{\frac{\pi(^{a}/_{W})}{cos(^{\pi a}/_{W})}}\right] \quad (2)$$

Where: E expressing the young's modulus, W corresponding to half width of sample, B referring specimen thickness and a_0 denoting half initial crack length.

The energy absorption at fracture U* measured from the area of load-displacement curve as plotted in Fig.3.

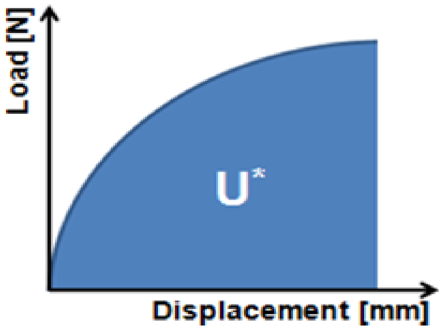


Fig. 3. Definition of U* for the calculation of J in the case of CCP specimen.

The crack growth Δa can be calculated through images obtained by the high resolution video camera placed on the fact of the CCP sample. The chosen sequence of high resolution video camera pictures representing the crack growth Δa in AA1050 H16 specimen is shown in Fig. 4.

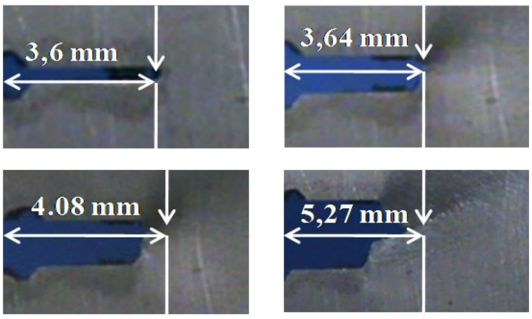


Fig. 4. A sequence of images revealed crack growth in case of unrolled AA 1050 H16.

The fracture toughness parameter $J_{0.2}$ was attained by the cross roads of the 0.2mm offset line with J-Δa curve as shown in ASTME1820 (see Fig.5). This parameter was used to understand the fracture toughness behavior of AA1050H16 in this study.

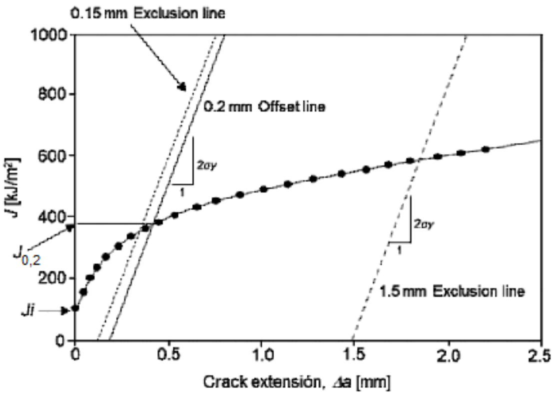


Fig. 5. Construction of the J-Δa resistance curve in accordance with ASTM E1820.

Fractographly analysis

Fractographic investigations were also effectuated on the fracture surfaces of the broken samples from tensile testing of different cold-rolled specimens.

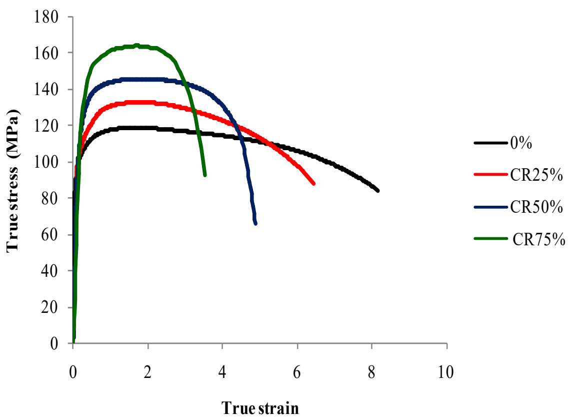
Electron fractography concerned the use of SH-3000 scanning electron microscope (SEM). Photographs were taken for the broken starting and cold-rolled specimens.

RESULTS AND DISCUSSION

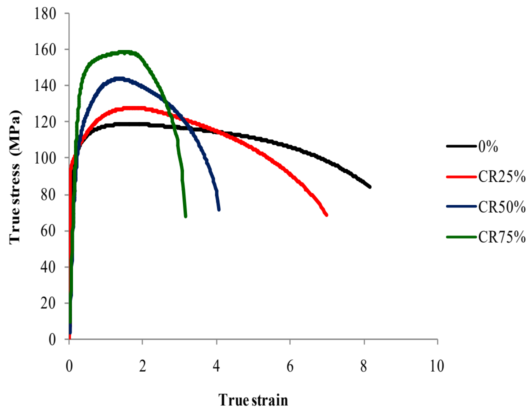
Cold rolling effect on the tensile properties

Fig.6 presents the comparison of the true stress-strain curves of starting and cold rolling AA1050H16 alloy along two directions (RD and TD). It can be seen that the true stress- strain curves ascended with increasing the percentage of cold rolling in two directions. The tensile proprieties of the starting and cold rolled specimens along two directions are shown in Table 2. The results notice that the cold rolling presents a considerable changement in the tensile properties of AA1050H16 in two directions (RD and TD). A long rolling direction (RD), the yield strength enhances from 91MPa to 136 MPa and the ultimate tensile strength increases from 119 MPa to 164 MPa after cold rolling percentage of 75%, representing by 33% for YS and 27% for UTS respectively. While, the elongation (A %) reduces from 8.17% to 3.51% after cold rolling percentage 75% presenting the important reduction by 57%. For transversal direction (TD), when the percentage of cold rolling increase, the ultimate tensile strength (UTS) increases from 117MPa to 127, 142 and 158 MPa (by 9 %, 21% and 35%) and the yield strength enhances from 92MPa to 104, 110 and 129 MPa (by 13%, by 20% and by 27%. Moreover, the percentage elongation (A %) decreases from 8,14% to 6,97%, 4,07% and 3,15%. The ultimate tensile strength (UTS) and yield strength (YS) of AA1050H16 have increased and the ductility (A %) has reduced with increasing the percentage of cold rolling from 0% to 75%.

These results show that the trend evolution of the mechanical tensile properties along two directions exhibits same characteristics with the tensile strength increasing and elongation is decreasing with the cold rolling percentage. The amendment of the mechanical tensile properties of AA1050H16 can mostly attributed to the many reasons. Primarily, with increment the cold rolling percentage, grains become more intensive and severely elongated through the rolling direction, which favorite the formation of the fiber texture in this direction leads to improve the tensile strength and reduce the ductility of alloy (Zhang et al., 2018 and Wang et al., 2015). As the rolling reduction increases, the secondary phase precipitates play a valuable role in enhancing the tensile strength through the precipitation strength mechanism. Secondly, the effect of strain hardening becomes more noticeable with increasing cold rolling percentage. This may lead to the rise of the dislocation density which brings to drop the ductility and increase tensile strength (Bo et al., 2015). This result is in agreement with those find by other researchers (Bora et al., 2020; Mhedhbi et al., 2017; Taktak et al., 2017; Tajally et al., 2010). Besides, when the direction modifies from rolling direction to transversal, the tensile strength has been dropped from 108MPa and 133MPa to 104MPa and 127MPa for 25%, from 116 MPa and 145MPa to 109 MPa and 138 MPa for 50% and from 136MPa and 164MPa to 129MPa and 158MPa for 75%. This result reveals that the anisotropy of the tensile strength of AA1050H16 alloy increases with the growth of cold rolling percentage. The greatest tensile strength was obtained in the rolling direction. This result is mentioned in various studies (Zhang et al., 2017; Tajally et al., 2010 and Dhara et al., 2016).



(a)



(b)

Fig. 6. True stress vs. strain curves of different cold rolling percentage along: a– RD; b– TD.

Table 2. Mechanical proprieties of the received and cold rolling AA1050H16 alloy along two directions (RD and TD)

CR (%)	Direction	YS[MPa]	UTS[MPa]	A(%)
0%	RD	91	119	8.17
	TD	92	117	8.14
25%	RD	108	133	6.44
	TD	104	127	6.97
50%	RD	116	145	4.89
	TD	109	138	4.07
75%	RD	136	164	3.51
	TD	129	158	3.15

Cold rolling effect on the hardness

The hardness amount of as-received and cold rolled AA1050alloy at diverse cold rolling reductions are illustrated in Table 3. It is evident that the hardness was remarkably enhanced with the cold rolling reduction. The result does accord with previous studies (Tajally et al.,2010; Bora et al., 2020; Jin et al. 2006). This is attributed to the following three reasons (Liu et al., 2018 and Gubiczaet al., 2007). For the first, the process of cold rolling leads to decrease the grain size and increase the grain boundary with the rise in terms of cold rolling reduction. The small grain size is more efficient at the mobility of dislocation resulting in increased hardness. Secondly, the density of dislocations was significantly increased during cold rolling. In addition, the existent dislocations prevent the nucleate and the motion of new dislocations which lead to the raised hardness of this alloy. Finally, the improvement of texture orientation due to process cold rolling played an important role in development of hardness and tensile properties of AA1050H16 alloy (Bora et al., 2020; Mhedhbi et al., 2017 and Jin et al., 2006).

Table 3. Values of Hardness for AA1050H16 with different percentage of cold rolling.

CR (%)	0%	25%	50%	75%
Hardness ($HV_{0.05}$)	48	57	74	115

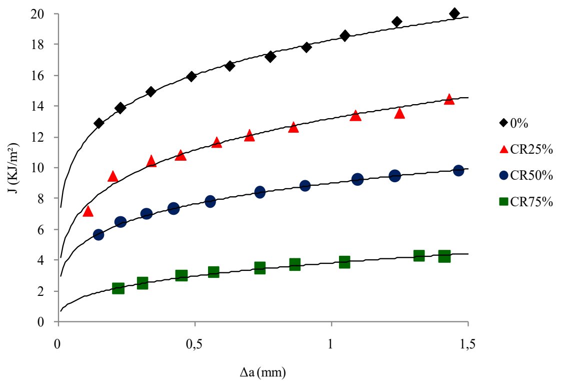
Cold rolling effect on the fracture toughness behavior

Fig.7 shows the experimental J-Δa curves of starting and cold rolled AA1050H16 in rolling and transversal direction (RD and TD). The fracture toughness parameter $J_{0.2}$ values obtained are given in Table 4. It can notice that the J-Δa curves get down after cold rolling in two directions. It is shown that the initiation toughness $J_{0.2}$ has been decreased speedily from 14.62 KJ/m² to 2.15 KJ/m² (by 85%) in RD (Fig.7.a) and from 11.5 KJ/m² to 1.05 KJ/m² (by 91%) in TD (Fig.7.b).These results found that the transition from ductile to brittle fracture in the cold rolled material can be ascertained by the remarkably reduced initiation toughness value compared to as-received material. It appears to indicate that cold rolling has adverse effect on the fracture toughness behavior, which has been referred to by others studies as well (Cosham et al.,2004; Tajally et al.,2010; Madi et al., 2020; Taktak et al.2021).

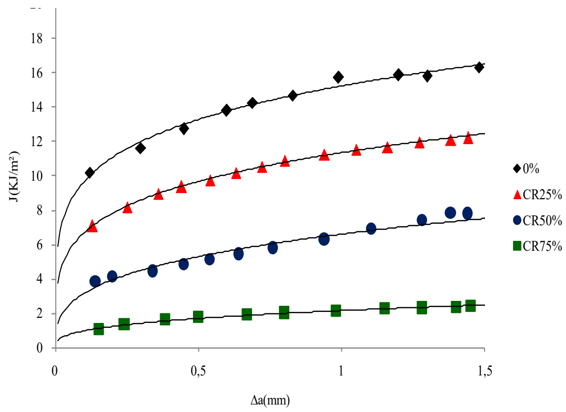
After cold rolling, the degree of anisotropy was also studied by fracture toughness test. It is founded that initiation toughness values has reduced from 10.12 KJ/m² to 8.18 KJ/m² (by 19.2%) when the direction changes from longitudinal to transverse for the samples after 25%CR, from 6.42 KJ/m² to 3.8 KJ/m² equal 40.8% of the samples after 50% CR and from 2.15 KJ/m² to 1.05 KJ/m² eagle 51.2% for the samples after 75%CR. In the rolling direction (RD) specimens the crack propagates through the grains while in the transverse direction (TD) specimens, the crack propagation is produced in the grain boundary in the rolling direction. The energy absorbed by the crack propagation in RD specimens is more important than that of TD specimen. Finally, it is confirmed that cold rolling has an extensive effect on anisotropy that is increased with the percentage of cold rolling (%CR). This result is conform those obtained by S. Iriç et al., 2017 and M.Tajally et al., 2010 in their investigates.

The transition from ductile failure to brittle failure in the cold-rolled AA1050H16 alloy can be justified by the remarkably lower fracture toughness parameter value as comparing to the as received alloy. The lower initiation toughness ($J_{0.2}$) for cold rolled specimens is revealed to cold rolling, can be attributed to elongated grains and dislocations produced during cold rolling (Thornton et al., 1985). In the metallic materials, micro-cracks and dislocations are the two more significant flaws negatively impacting fracture toughness. The brittle fractures are usually related to defects and cracks in the alloy and they are also defined by an absence of severe plastic deformation and a less energy absorption (Thornton et al., 1985). Generally, the principal difference between ductile and brittle failure may be ascribed to the quantity of the plastic deformation that the metal submitted before fracture produced. Brittle materials exhibit little or no plastic deformation while the ductile materials show a high amount of plastic deformation before failure.

We now explain the brittle fracture mechanism in the cold rolled AA1050H16 alloy by referring to our mechanical test data. The cold rolling leaded to rise in the yield strength; and resulted in absence of plastic deformation; which also led to a reduction of initiation toughness. There is an inverted relationship between the yield stress and the energy propagation. Therefore, it is logic to confirm that the cold rolling in AA1050H16 alloy leads to low the initiation toughness and enhances the brittle failure behavior.



(a)



(b)

Fig. 7. J-Δa curves of different cold rolling percentage along: a–RD; b– TD.

Table 4. Values of fracture toughness parameter $J_{0.2}$ for the as-received and cold rolled AA1050-H16.

CR (%)	Direction	$J_{0.2}$ (KJ/m²)
0%	RD	14.62
	TD	11.5
25%	RD	10.12
	TD	8.18
50%	RD	6.42
	TD	3.8
75%	RD	2.15
	TD	1.05

Cold rolling effect on the fracture behavior

In order to comprehend the mechanical behavior of the materials tested, it is important to analyze the rupture surfaces. Fractography examinations of the as-received and cold rolled specimens were performed on tensile fracture surface samples by using SEM fractographs. Fig 8 illustrates fractography pictures of as-received and cold rolling materials. For the as-received material samples (Fig.8.a), a high number of dimples of various sizes and forms which reveal the physical mechanism of ductile damage: nucleation, growth and coalescence of micro voids. Generally, in aluminum alloy, the various dimples are started as microvoids in the second-phase particles (Mhedhbi et al. 2017 and Jin et al., 2006). For that, the form and size of dimples are ascribed to the form and size of the second particles.

The failure surface of tensile of the 25% to 75% cold rolled samples (fig8.b, c, d) also showed many dimples slightly extend in the direction of the axial tensile stress and some quasi-cleavage areas. It found that the quality of dimples reduced and the quasi-cleavage areas increased with the rise in terms of the amount of cold rolling reduction due to the ductile to brittle failure. In metallic metals like AA1050 alloy, the dislocation mobility stays high, although at low temperature and the metal remains relatively ductile.

Hence, the fracture morphology presents a few dimples and some quasi-cleavage areas due to brittle fracture behavior of the alloy. Chen et al.2017 and Tajalli et al., 2010 have suggested that the principal factor favors the transition from dimple cracks to cleavage is caused by the rise of the local tensile stress forward of the crack which is led by the growth of the triaxiality of stress and the obvious normal stress on the residual ligament.

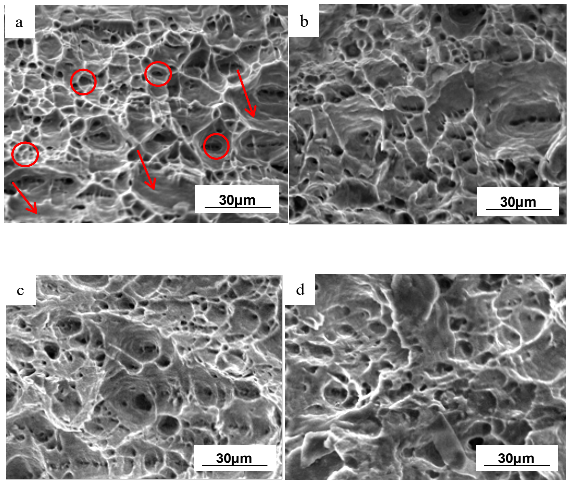


Fig.8. SEM images of AA1050 H16 alloy before and after cold rolling: (a) as received AA1050H16; b– CR 25%; c– CR 50% and d– CR75%.

CONCLUSIONS

In this work, the effect of cold rolling on the mechanical properties and fracture toughness behaviour was investigated and the flowing conclusions were established:

- The cold rolling has an extensive effect on mechanical properties of AA1050H16. During the cold rolling, the ultimate tensile strength (UTS), yield strength (YS) and hardness increase but the ductility reduces with increasing the percentage of cold-rolling. The cold rolling leads to the strengthening and the embrittlement of AA1050H16 alloy.

- The decrease of the fracture toughness parameter $J_{0.2}$ with the increase of cold rolling shows that the profound effect of cod rolling in the fracture toughness behavior of the alloy. The cold rolling reduces the fracture resistance to damage of AA1050H16.

- The SEM images of the starting and cold rolled AA1050H16 alloy proves that the cold rolling conducts to transition the fracture mechanism from ductile to brittle of AA1050H16 alloy.

- The cold rolled AA1050H116 alloy with 25% and 50% present a ductile behavior however the cold rolled alloy with 75% shows a brittle behavior.

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