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EXPERIMENTAL INVESTIGATION INTO THE EFFECT OF COLD ROLLING ON FRACTURE TOUGHNESS AND MECHANICAL PROPERTIES OF AA5754 H111 ALUMINIUM ALLOY

Summary

The paper deals with the experimental examination in to fracture toughness and mechanical behaviour of an AA5754 H111 aluminium alloy sheet during cold rolling reduction. The fracture toughness parameter $J_{0.2}$ of the AA5754 H111 aluminium alloy before and after cold rolling was estimated by conducting a ductile tearing test using centre-cracked panel (CCP) specimens along two directions, rolling direction (RD) and transversal direction (TD). The conventional tensile tests in two directions and microhardness tests were also used to investigate mechanical properties of unrolled and rolled AA5754 H111 aluminium alloy. The findings revealed a significant effect of cold rolling on the fracture toughness parameter and the mechanical properties of the AA5754 H111 aluminium alloy along the RD and TD. A fast increase in strength and hardness and a sharp drop in the fracture toughness parameter $J_{0.2}$ and ductility were recorded with a rise in the amount of cold rolling reduction. The greatest strength was obtained along the RD and the highest ductility was found along the TD.

Key words: *AA5754 H111 aluminium alloy, cold rolling, mechanical properties, fracture toughness*

1. Introduction

The 5XXX series aluminium alloys (non-heat-treatable Al-Mg) have been used extensively in the automotive industry [1-5]. They are widely used for marking automotive parts, such as panel components, due to their superior and desirable properties, namely, low density, a suitable combination of strength and ductility, excellent corrosion resistance and satisfactory fracture toughness [6-11].

Cold rolling of an aluminium alloy sheet is a very common process used in manufacturing automotive panel components. During this process, aluminium alloy sheets are submitted to a significant plastic strain, thus modifying the mechanical and fracture toughness behaviour [12, 13]. Numerous studies demonstrated that cold rolling has a profound influence on mechanical properties of aluminium alloys. Wang et al.[14], Sarkar et al.[15],Jin et al.[16] and Wowk et al.[17] showed that cold rolling results in the improvement of tensile strength and hardness of the material and in a decrease in ductility.

An overview of the literature reveals that although many studies explored the cold rolling effect on fracture toughness of steels, there is a scarcity of information regarding aluminium alloys [18-21]. Previous steel-related research indicated that cold rolling has an important impact on fracture toughness behaviour [22]. Cold rolling reduces crack growth resistance, as well as crack initiation resistance.

In this study, the effect of cold rolling on the fracture toughness behaviour and mechanical properties of AA5754 H111 aluminium alloys was addressed. AA5754 H111 aluminium alloy sheets underwent different amounts of cold rolling reduction in thickness (25%, 50% and 75%). The conventional tensile test was performed in two directions, the rolling direction (RD) and the transversal direction (TD) in order to identify tensile properties of the unrolled and rolled AA5754 H111 aluminium alloy. Therefore, the Vickers microhardness was determined for this alloy before and after the cold rolling process took place. Moreover, the fracture toughness parameters of the unrolled and rolled alloy were explored utilizing the fracture toughness test of centre-cracked panel (CCP) specimens along the two directions (RD and TD).

2. Materials and methods

2.1 Materials and cold rolling process

In the present study, the specimens were taken from a 3mm thick AA5754 H111 aluminium alloy sheet. The chemical composition of the alloy is given in Table 1. The H111 temper means that the used alloy was hardened by work hardening followed by recrystalization annealing in order to recover ductility.

Table 1 Chemical composition of AA5754 H111 aluminium alloy (wt %)

Element	Al	Mg	Mn	Fe	Si	Cr	Zn	Ti	Cu
Composition (wt%)	Balance	3.6	0.5	0.4	0.4	0.3	0.2	0.15	0.1

The original sheet specimens of the AA5457 H111 aluminium alloy with dimensions of 300 mm (length) x 200 mm (width) x 3 mm (thickness) were cold rolled in a laboratory rolling mill to the thickness reductions of 25%, 50% and 75% and the thickness of the sheet was reduced from 3 to 2.25, 1.5 and 0.75 mm, respectively.

2.2 Microstructure

The microstructures of the unrolled and rolled specimens were analyzed using optical microscopy (OM). Firstly, all specimens were cold coated with an epoxy resin, and then pre-polished with 240, 400, 600, 1000 and 1200 grit silicon carbide grinding papers. After wards, they were manually polished using a 3µm diamond spray, followed by using a 1µm alumina suspension to get mirror surfaces. Finally, the specimens were etched in Keller's solution (190ml H_2O, 3ml HCl, 2ml HF and 5ml HNO3).

2.3 Fracture toughness evaluations

CCP specimens were used to measure the fracture toughness parameters of the AA5457 H111 aluminium alloy before and after the process of cold rolling. Figure 1 depicts dimensions and geometry of the CCP specimens. A wire cut machine was used to process the specimens in both directions, the RD and the TD, to highlight the anisotropy in the fracture toughness parameter. Then, the specimens were pre-cracked to 5mm (a_0/W=0.5) by applying the fatigue test, where a_0 is the half initial crack length and W is the half width of the specimen.

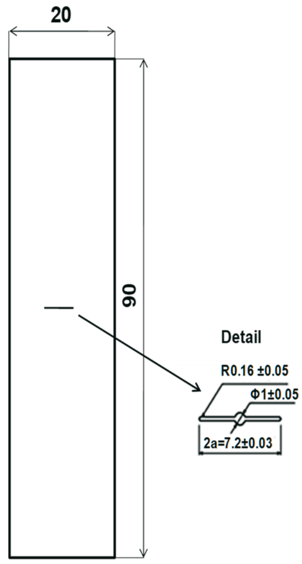


Fig. 1 Dimensions and geometry of CCP specimens (in mm).

The ASTME1820 standard test method using the single specimen technique was used to construct the *J*-Δ*a* curve for the unrolled and rolled AA5754 H111 sheets. The fracture toughness tests were performed by a 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.

J values were calculated by using equation 1, [23]:

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

In the case of CCP specimens, the value of the stress intensity factor K is suggested by equation 2, [24],

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

where E is Young's modulus, W is the half width of the specimen, B is the thickness of the specimen and a_0 is the half initial crack length.
U^* is the energy determined under the load-displacement curve record as plotted in Figure 2.

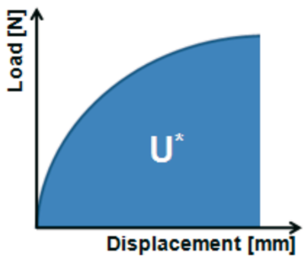


Fig. 2 Energy absorption at fracture U^* for a CCP specimen.

The Δ*a* value of the crack extension can be estimated from the images of the fracture surface of the CCP specimens acquired by a high-resolution video camera situated in front of the specimen. A chosen sequence of the high-resolution video camera pictures representing the crack growth Δ*a* in the AA5754 H111 specimen is shown in Figure 3.

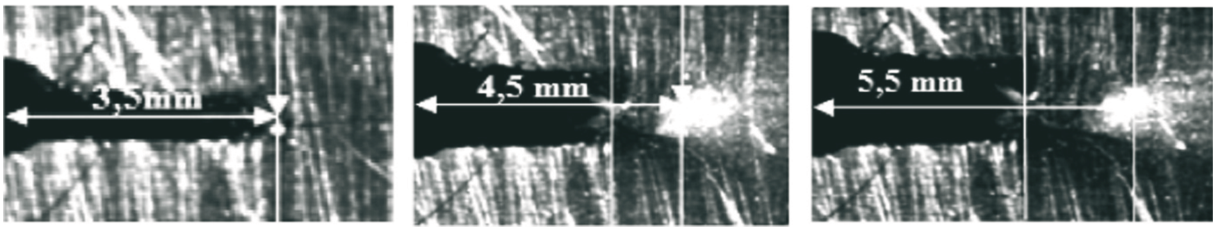


Fig. 3 A sequence of images revealed crack extension in AA 5754 H111 aluminium alloy specimen.

The crack initiation toughness $J_{0.2}$ is the fracture toughness value at the point where the initiation of stable crack propagation (critical crack length) was detected [25]. It was specified by the intersection of the 0.2 mm offset line with the J-Δa curve according to ASTME1820 [26] (see Figure 4).

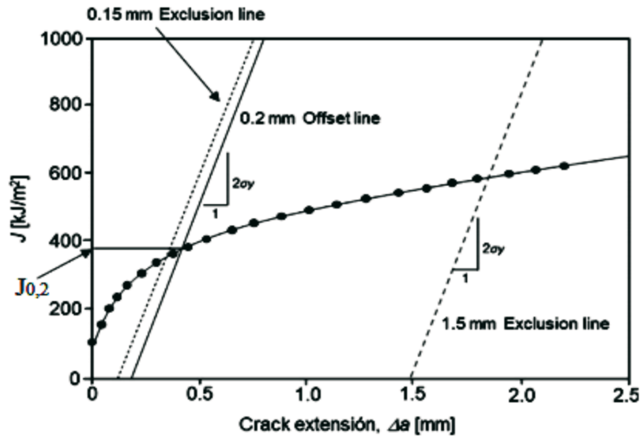


Fig. 4 J-Δa resistance curve in accordance with ASTM E1820.

2.4 Evaluation of mechanical properties

Tensile and hardness tests were performed to study the mechanical behaviour of the AA5754 H111 aluminium alloy. Tensile test specimens were cut and machined according to the NF EN 10002-1 standard (see Figure 5) in the RD and TD to examine the anisotropy of the tensile properties. At room temperature, conventional tensile tests were conducted by using a universal tensile machine LLOYD of capacity 50 kN at a crosshead speed of 10 mm/min. Extensometer with a 25 mm length was installed on the gauge section to measure the strain in the longitudinal direction (see Figure 6). Three unrolled and three rolled specimens of the AA5754 H111 aluminium alloy were tested. Figure 6 depicts the experimental placement of the tensile specimens. Furthermore, hardness measurements were performed by using a Vickers machine. All specimens were tested with a 50 g weight applied for 15 seconds. Ten measurements were made for each specimen.

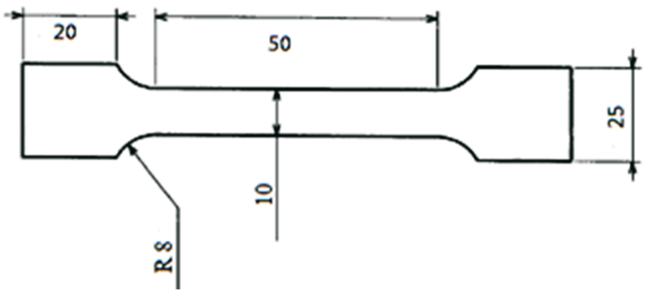


Fig. 5 Schematic of a tensile specimen (dimensions in mm).

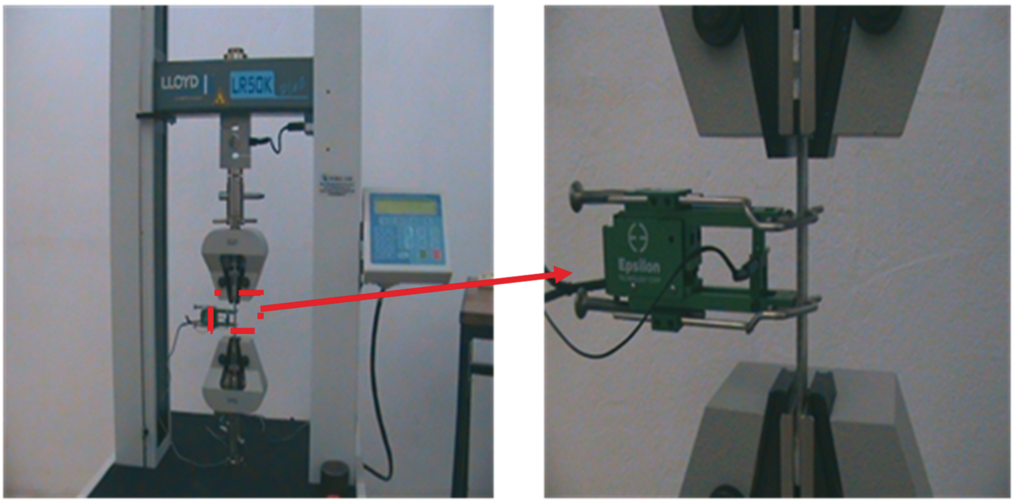


Fig. 6 Experimental setup of tensile test.

3. Results and discussion

3.1 Microstructure

Optical microstructures of the cold-rolled AA5754 H111 sheets at 0% (unrolled), 25, 50 and 75% are illustrated in Figure 7. The microstructure of the aluminium matrix (α (Al)) and second phase (Al_6Mn and Mg_2Si) distribution are shown for all specimens. The increase in the amount of cold rolling generated even more elongated and refined microstructure. Also, the number of the elongated distributed second phase particles was increased. The same results are reported in earlier studies [14,16,17].

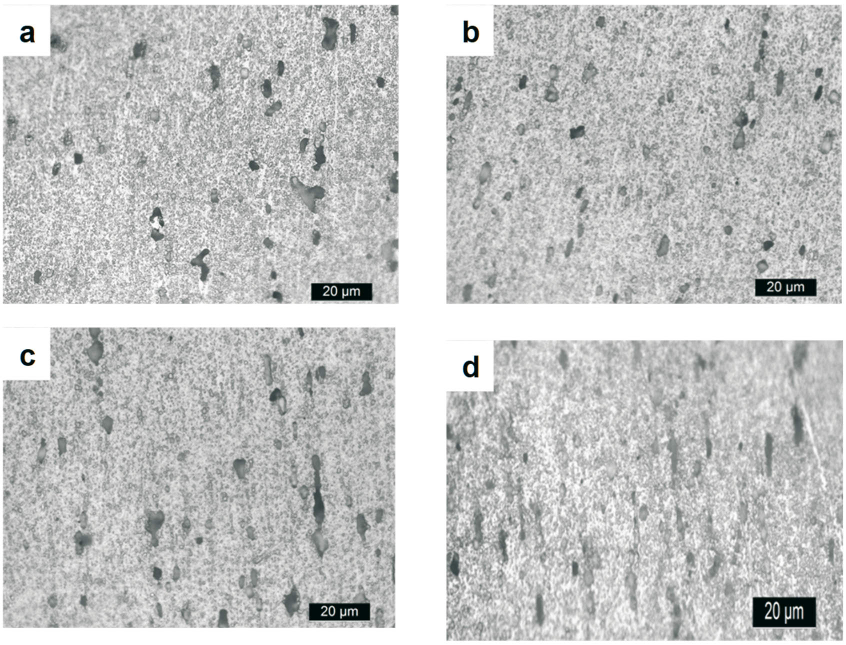


Fig. 7 Optical microstructure of (a) unrolled specimen, (b) rolled specimen after 25% reduction, (c) rolled specimen after 50% reduction, (d) rolled specimen after 75% reduction.

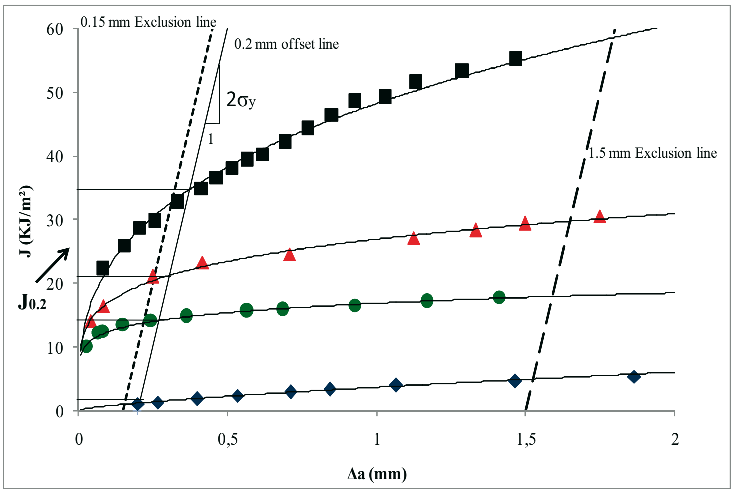
3.2 Fracture toughness behaviour

Figure 8 illustrates experimental *J*-Δ*a* curves of the AA5754 H111 aluminium alloy specimens with different reductions in the RD and the TD. The resistance at the crack initiation $J_{0.2}$ values for the unrolled and cold rolled AA5754 H111 specimens is given in Figure 9. It can be seen from these two directions that the *J*-Δ*a* curves decreased with a rise in the amount of the cold rolling reduction.

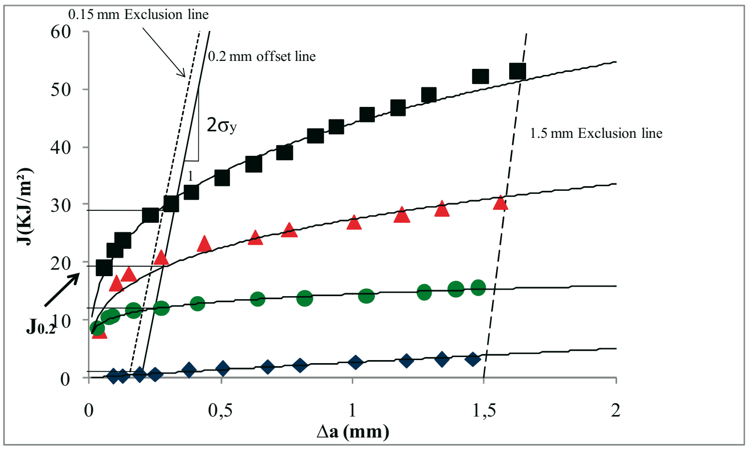
After the cold rolling reduction to 75%, $J_{0.2}$ decreased rapidly from 34.6 kJ/m² to 1.02 kJ/m², indicating a decrease of 97% in the RD (see Figure 8.a). Besides, the value of 0.89 kJ/m² is determined for this fracture toughness parameter through the rolling reduction to 75%, representing a 94% reduction in the TD (see Figure 8.b). These trends show that the crack initiation toughness ($J_{0,2}$) of AA5754 H111 is notably diminished by the process of cold rolling. Also, the cold rolling is performed to reduce the fracture toughness resistance in the investigated AA5754 H111 aluminium alloy. These results show that the transition from ductile to brittle fracture in the cold rolled alloy can be verified by the remarkably lower crack initiation toughness value of the cold rolled alloy compared to as-received alloy. It appears that cold rolling has an adverse effect on the fracture toughness behaviour, which reported by other studies as well [12, 18, 27].

After cold rolling, the degree of anisotropy was also studied by applying the fracture toughness test. It is found that the initiation toughness values have reduced from 25.7 kJ/m² to 21.4 kJ/m² (by 16.7%) when the direction changes from longitudinal to transverse for the specimens after 25% cold rolling reduction, from 14.2 kJ/m² to 12.3 kJ/m² (by 13.4 %) of the specimens after 50% cold rolling reduction and from 1.02 kJ/m² to 0.89 kJ/m² (by 12.8 %) for the specimens after 75% cold rolling reduction (see Figure 9). In the RD specimen, crack propagation passes through the grains during propagation, while in the TD specimen, crack propagation occurs in the grain boundary along the rolling direction. The energy absorbed by the crack propagation in the RD specimens is more important than that of the TD specimens [27]. Finally, it is confirmed that the process cold rolling has an extensive effect on anisotropy that is increased with the percentage of cold rolling reduction. This result confirms the results obtained in [27, 28].

The transition from ductile failure to brittle failure in the cold-rolled AA5754 H111 aluminium alloy can be justified by the remarkably lower fracture toughness parameter value in comparison to the as-received aluminium alloy. The lower crack initiation toughness ($J_{0.2}$) for the cold rolled specimens is attributed to elongated grains and dislocations produced during the cold rolling process [29]. In the metallic materials, micro-cracks and dislocations are two 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 low energy absorption [29]. Generally, the principal difference between ductile and brittle lies in the quantity of the plastic deformation that the metal was subjected to before it fractured. Brittle materials exhibit little or no plastic deformation while ductile materials show a high amount of plastic deformation before failure. We are now going to explain the brittle fracture mechanism in the cold rolled AA5754 H111 aluminium alloy by referring to our mechanical test data. The cold rolling resulted in an increase in yield stress and a lack of plastic deformation, which also led to a loss in crack initiation toughness. There is an inverse relationship between the yield stress and the energy propagation. Therefore, it is logical to state that cold rolling in the AA5754 H111 aluminium alloy leads to a low crack initiation toughness ($J_{0.2}$) and enhances the brittle failure behaviour. This is also in accordance with the results reported in [27].



(a)



(b)

Fig. 8 *J*- Δ*a* curves of AA5754 H111 aluminium alloy with different cold rolling reductions in RD (a) and TD (b).

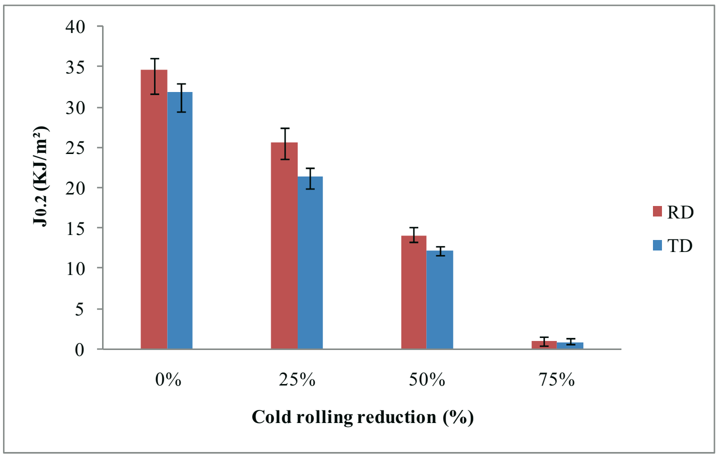


Fig. 9 Variation of the crack initiation toughness $J_{0.2}$ of AA5754 H111 aluminium alloy with different cold rolling reduction in RD and TD.

3.3 Mechanical properties

The evaluation of the ultimate tensile strength (UTS), yield strength (YS) and elongation (A %) of the AA5754 H111 aluminium alloy specimens changing with an increase in the cold rolling reduction along two directions (RD and TD) is shown in Figure 10. The results demonstrate that the cold rolling process causes a considerable change in tensile characteristics of the AA5754 H111 aluminium alloy in two directions the RD and the TD. With the increase in the cold rolling reduction from 0% to 75%, the ultimate tensile strength and yield strength of the AA5754 H111 aluminium alloy grew steadily, while the ductility decreased.

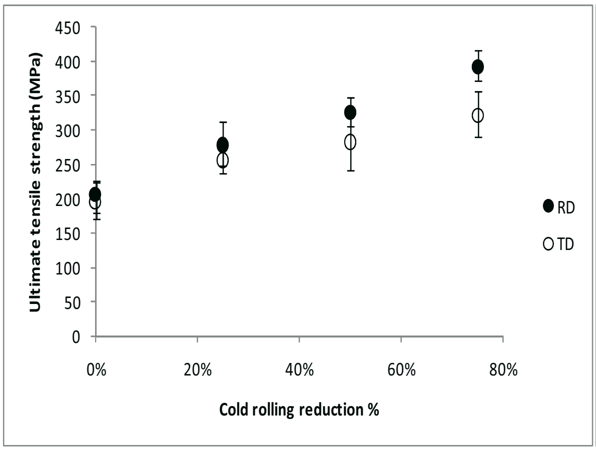
After the cold rolling reduction of 75 % in the RD, the ultimate tensile strength increases from 206 MPa to 392 MPa and yield strength increases from 100 MPa to 265 MPa, corresponding to 91 % for UTS and 165 % for YS, respectively. However, the elongation reduces from 16.5 % to 1.95% (decrease of 88%).

For the TD, when the cold rolling reduction increases from 0% to 75%, the values of UTS rise from 198 MPa to 255 MPa, 282 MPa and 320 MPa (increase of 62%) and the values of YS increase from 97 MPa to 140 MPa, 171 MPa and 208 MPa (increase of 114%). Nevertheless, the elongation values (A %) decrease from 16.87% to 8.7%, 6.23% and 3.94% (reduction of 77%). The following data show that, along the two directions (RD and TD), the behaviour of AA5754 H111 aluminium alloy after cold rolling is characterized by higher strength and lower ductility. Hence, cold rolling has a considerable and equivalent effect on the tensile characteristics of the AA5754 H111 aluminium alloy in both, the rolling and the transverse directions.

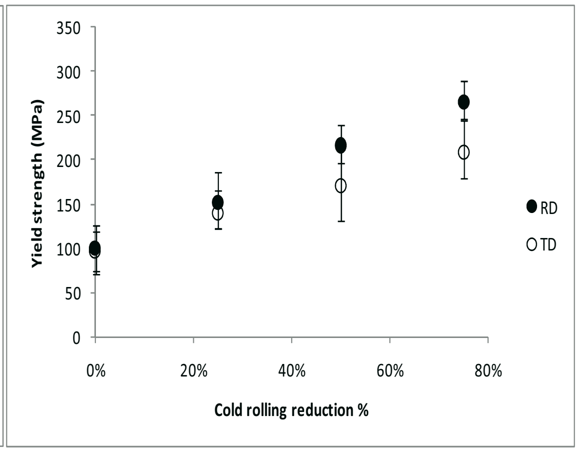
These results show that the trend evolution of the mechanical tensile properties along two directions exhibits the same characteristics with the tensile strength increasing and elongation is decreasing with the cold rolling reduction percentage. The change in the mechanical tensile properties of the AA5754 H111 aluminium alloy can be attributed to many reasons. Firstly, with an increase in the cold rolling reduction percentage, grains become severely elongated along the rolling direction, which favours the formation of fiber texture in this direction and improves the tensile strength and reduces the ductility of the alloy [14, 30, 31]. As the cold rolling reduction increases, the secondary phase precipitates play a valuable role in enhancing the tensile strength through the precipitation strengthening mechanism.

Secondly, the effect of strain hardening becomes more noticeable with an increase in the cold rolling percentage. This may lead to a rise in the dislocation density which results in a drop in ductility and an increase in tensile strength [14]. This result is in agreement with the obtained by other researchers [32, 33, 16].

Furthermore, as can be seen from Fig. 8a, 8b and 8c, when the direction changes from RD to TD, the ultimate tensile strength and yield strength drop from 278 MPa and 152 MPa to 255 MPa and 140 MPa for 25% cold rolling reduction, from 325 MPa and 216 MPa to 282 MPa and 171 MPa for 50% cold rolling reduction and from 392 MPa and 265 MPa to 320 MPa and 208 MPa for 75% cold rolling reduction. The elongation rises from 7.67% to 8.7% for 25%, from 4.47% to 6.23% for 50% cold rolling reduction and 1.95%to 3.34% for 75% cold rolling reduction. The obtained results demonstrated that the anisotropy of tensile properties of the AA5754 H111 aluminium alloy increases with an increase in the cold rolling reduction. Higher tensile strength and a low ductility are observed in the RD. This result is mentioned in various studies [16, 31, 34,35].



(a)



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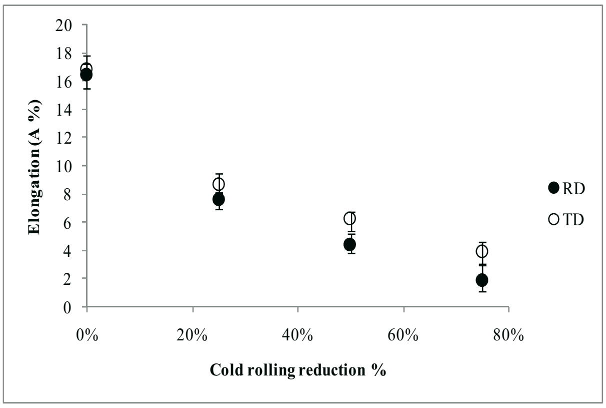

(c)

Fig. 10 The influence of cold rolling reduction on (a)ultimate tensile strength, (b) yield strength and (c) elongation of AA5754 H111aluminium alloy along two directions (RD and TD).

3.4 Hardness measurements

Figure 11 presents the microhardness curve of the AA5754 H111 aluminium alloy under different rolling reductions. The hardness of the material increases significantly as the cold rolling reduction decreases. Such data indicate the presence of the work hardening in the AA5754 H111 aluminium alloy during cold rolling. The micro hardness is near $165HV_{0.05}$, which is roughly two times that of the unrolled AA5754 H111 aluminium alloy, suggesting that hardness can be improved by the cold rolling process. This can be attributed to the following reasoning [27, 36, 37]. First, cold rolling leads to a refinement of the microstructure which increases the grain boundary. The smaller grain size is more capable of blocking the movement and multiplication of dislocation leading to increased hardness. Secondly, during the cold rolling process, the density of dislocation is significantly enhanced. Moreover, the current dislocations impede the movement and nucleation of new dislocations which engender the increase in the hardness of this alloy. In addition, the formation of texture orientation during cold rolling plays an important role in the improvement of hardness and mechanical properties. Finally, an increase in the number of elongated second phase particles (see Figure 7) due to cold rolling results in improved hardness.

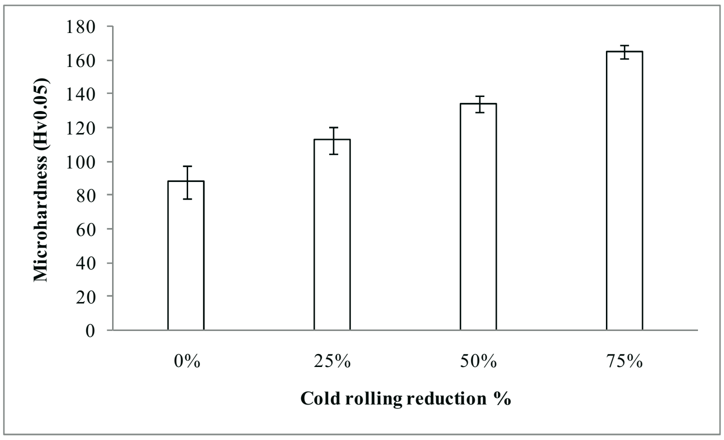

Fig. 11 Variation of hardness of AA5754 H111 aluminium alloy with different cold rolling reduction.

4. Conclusion

This study allows a deeper insight in to the cold rolling effect on the mechanical properties and fracture toughness resistance of the AA 5754 H111 aluminium alloy.

The essential conclusions drawn in this investigation can be stated as follows:

1. A significant increase in yield strength, tensile strength and hardness with an increase in the amount of cold rolling reduction, despite the important decrease in elongation of the cold rolled AA5754 H111 aluminium alloy, can be interpreted in terms of the occurrence of the strain hardening phenomenon during the cold rolling process. The cold rolling results in the strengthening of the cold rolled AA 5754 H111 aluminium alloys. The results confirm that cold rolling has an extensive effect on the mechanical behaviour. The highest strengths are determined for all cold rolled specimens in the RD.
2. A remarkable drop in the values of the crack initiation toughness ($J_{0.2}$) of the AA5754 H111 aluminium alloy was reported with an increase in the amount of cold rolling reduction. This result demonstrates that cold rolling generates a decrease in terms of the fracture toughness resistance of the AA5754 H111 aluminium alloy.
3. The AA5754 H111 aluminium alloy cold rolled at 25% and 50% reductions shows ductile behaviour however the alloy cold rolled at a 75% reduction shows brittle behaviour.

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