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Effects of thickness and surface roughness on mechanical properties of aluminum sheets †

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Abstract

The effect of thickness on the mechanical properties of Al 6K21-T4 sheet specimens under uniaxial tension was investigated. In order to reduce the thickness of the specimens without changing the microstructure and grain size, chemical etching was carried out, resulting in Al sheets ranging from 0.40 mm to 1.58 mm in thickness. Additionally, the effect of surface roughness was determined by finite element (FE) calculations performed using FE code MARC 2007. Tensile specimens of varying surface roughness were modeled and simulated. An analysis of the combined effects of the thickness and surface roughness revealed that the yield and tensile strengths decreased when the number of grains over the thickness was decreased. The ductility also decreased when reducing the thickness. An FE simulation showed that both the surface roughness and thickness affected the flow-curve shape. Moreover, the effect of the surface roughness tended to increase when decreasing the sheet thickness of specimens having the same roughness.

Keywords: Grain size; Size effect; Surface roughness; Aluminum sheet; Uniaxial tension; Mechanical properties

1. Introduction

With the increasing use of miniaturized parts across many industrial fields such as medical equipment, electronics, robots, and automobiles, the forming of parts of relatively small dimensions is playing an increasingly important role. However, in the forming of such parts, several additional and important factors come into play, including the higher level of accuracy required of tools used in material handling and positioning, along with changes in the mechanical properties of formed parts themselves [1].

Many known phenomena in bulk metal mechanics, such as material strength, ductility, and localized necking, need to be reconsidered when the ratio between the component and the grain size is very small. The grain size and distribution, the strain gradient, and the free surface effect must also be considered for accurate measurement of the mechanical properties of miniaturized materials [2].

The effect of grain size on metals strengths has already been investigated in various studies; the linear dependency of the yield stress on the inverse of the square root of the grain size now is well known as the Hall-Petch relation. The existence of precipitates in metal also increases metal strength, by interrupting the movement of dislocation. Thus, grain size and precipitate distribution are both important factors impacting the mechanical properties of metal, and these effects, significantly, are enhanced when the material is miniaturized. If miniaturized materials have the same grain size and precipitate distribution, the effects of size need to be considered in order to accurately predict their mechanical properties. In particular, two effects need to be examined. First, the ratio of the grain size to the sheet thickness is crucial, as when the sheet thickness is decreased, the mechanical properties of the individual grains come to dominate the properties of the sheet. Second, reducing the sheet thickness means that the grains on the free surface are less constrained and more easily deformed at a substantially lower flow stress than is the case in the bulk state [3-9].

To date, most research on the effects of size has been conducted using rolling and heat treatment to change the grain size and sheet thickness [3-5]. A major drawback of this methodology though, is that different heat treatment temperatures can result in the formation of different oxide layers on specimens, and in different initial dislocation densities, making precise measurement of mechanical properties difficult.

Also, it has been reported that surface roughness mainly affects the fatigue life and contact problem and that there is no significant effect on static mechanical properties such as strength and ductility. However, the effect of surface rough-

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ness on a material's mechanical properties is magnified when that material is miniaturized. In a recent study, the effect of roughness on internal stress measured in a tensile test was investigated using the finite element method (FEM) [10]. Yet, the research focused on a very small area, as the roughness was within the micron range, thereby limiting the study of the overall behavior of the tensile specimen. And, although a number of studies have been conducted to demonstrate the relationship among grain size, roughness, and limit strains [11-13], they did not consider the initial effect of roughness on mechanical properties.

In an effort to fill, at least partially, the research gap, the present study used, in place of the conventional rolling and heat treatments, a chemical etching method to reduce the thickness of an aluminum sheet. After the chemical etching, no significant changes were found in the dislocation density, the direction of the lattice, or the oxide layer. Plus, chemical etching is very easy to perform, inexpensive. Finally, the FEM was used to investigate the effect of the surface roughness on the mechanical properties.

2. Experimental

The material used in this investigation was aluminum 6K21-T4, the chemical composition of which is shown in Table 1. Chemical etching was used to reduce the thickness of the sheet, and no significant changes in the microstructure and grain size were observed during or after the etching. Rolled sheets had been sliced into the required dimensions (200 mm × 150 mm × 1.58 mm) using abrasive cutters, after which they were deposited in an aluminum etch type D etching liquid (phosphoric acid 60%, sodium-M-nitrobenzene sulfonate 7%, acetic acid 3%, distilled water balance). Final sheets of the different thicknesses of 1.40 mm, 1.04 mm, 0.72 mm, and 0.40 mm were formed by varying the deposition time. After etching, the edge thicknesses of the sheets were smaller than the thicknesses of the inner areas, as the etching velocity was faster at the edges. Therefore, the specimens used for observation of the microstructure and for the tensile test were obtained from the inner areas of the sheets.

The specimens were prepared as follows. After cutting, the surface was mechanically polished and etched. The microstructure was then analyzed using an optical microscope (OM), and the grain size was measured as per ASTM E112. Meanwhile, the surface roughness was measured using a roughness tester (Taylsurf PGI 120) before and after chemical etching, as per KS B 0161. For the tensile test specimens, the sheets were sliced, machined to the required dimensions, and then prepared as per ASTM E8 (Fig. 1). The tensile test was carried out in a universal testing machine (Instron 5569), employing a test velocity of 0.0167 mm/s. An extensometer of 25 mm gauge length was used for accurate strain measurement. The tests were conducted three times, using the 0.2% offset yield strength, to ensure reproducibility.

As it is difficult to achieve a desired surface roughness using chemical etching, additional machining or grinding is necessary. However, machining can generate residual stress that affects the mechanical properties of the specimen surface, which complicates any investigation of the effect of surface roughness on mechanical properties. Therefore, the FEM was adopted to investigate only the effect of the surface roughness. The simulation was carried out after making FE models of specimens with thicknesses of 1.58 mm and 0.40 mm and two types of surface roughness: no surface roughness (i.e. a flattened surface) and periodic surface roughness. The FE model used in this study is illustrated in Fig. 2. For computational efficiency, a 1/8-scale symmetric model, generally preferred, was employed in the numerical simulation. The fine mesh size was determined to be small enough for the simulation of necking in the gauge length. The same mesh size was used in all the models to minimize the mesh-size effect, and the material was assumed to deform plastically with isotropic hardening, according to the Von-Mises yielding condition. If the mesh reached the ductile fracture criteria, it was eliminated from the model, like a crack in a real tensile specimen. The FE code MARC 2008 was used, along with the flow curve obtained

Table 1. Chemical composition of 6K21-T4 used in present study (wt%).

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.99	0.15	0.01	0.07	0.54	0.01	0.01	0.01	Bal.

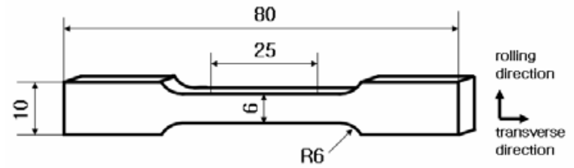


Fig. 1. Sketch of sample geometry for tensile test (unit: mm).

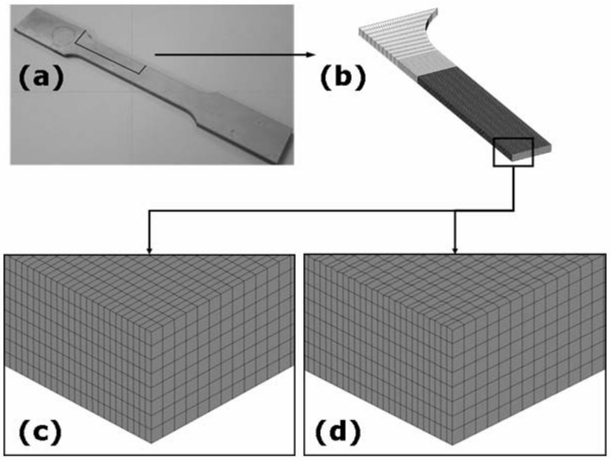


Fig. 2. Finite element (FE) modeling of tensile specimen: (a) examined tensile specimen, (b) 1/8th of sample geometry used for symmetrical calculation, (c) flattened surface, and (d) periodic notch used to investigate effect of surface roughness.

from the tensile test of the 1.58 mm-thick specimen. The modified Cockroft-Latham criteria [14] were utilized to predict the exact ductile fracture, and the effect of the thickness and surface roughness on ductility was investigated.

$$\int_0^{\bar{\varepsilon}_f} \frac{\sigma^*}{\bar{\sigma}} d\bar{\varepsilon} = C \tag{1}$$

where $\bar{\sigma}$ is the equivalent stress, $\bar{\varepsilon}$ the equivalent strain, σ^* the highest tensile stress, and $\bar{\varepsilon}_f$ the fracture strain obtained from the tensile test [15].

$$\bar{\varepsilon}_f = \frac{2}{\sqrt{3}} \ln \frac{h_o}{h_f} + \frac{2n}{\sqrt{3}}(\sqrt{3}-1) \tag{2}$$

where h_o is the initial thickness of the specimen, h_f the final thickness after the tensile test, and n the work-hardening exponent.

3. Results and discussion

3.1 Effect of thickness

The microstructures of the 1.58 mm- and 0.72 mm-thick specimens are shown in Fig. 3. No significant difference was found between the microstructures or the grain sizes of the two specimens, the average grain size being about 40 μm for both. Thus, it could be concluded that the chemical etching did not have any effect on the microstructure or grain size.

The symbol λ, commonly used to investigate the effect of grain size, represents the ratio between specimen thickness (t) and average grain size (d):

$$\lambda = \frac{t}{d} \tag{3}$$

For λ <1, there is a single grain over the specimen thickness, and for λ>1, there are multiple such grains. The present study considered only the case of λ>1 in examining the effects of grain size and the surface roughness on mechanical properties.

The symbol α, used as a parameter in studies on the effect of grain size, stands for the volume fraction of grains having a free surface:

$$\alpha = 1 - \frac{(w-2d)(t-2d)}{wt} \tag{4}$$

where w is the width of the specimen.

As thickness decreases, the relative surface area of a specimen increases. That is to say, when α decreases, the effect of the surface on the mechanical properties is enhanced.

Specimens fractured in the tensile test are shown in Fig. 4, and the pertinent engineering stress-strain curves are plotted in Fig. 5. The strength indicated in the engineering stress-strain curves changed when the thickness was reduced, signaling

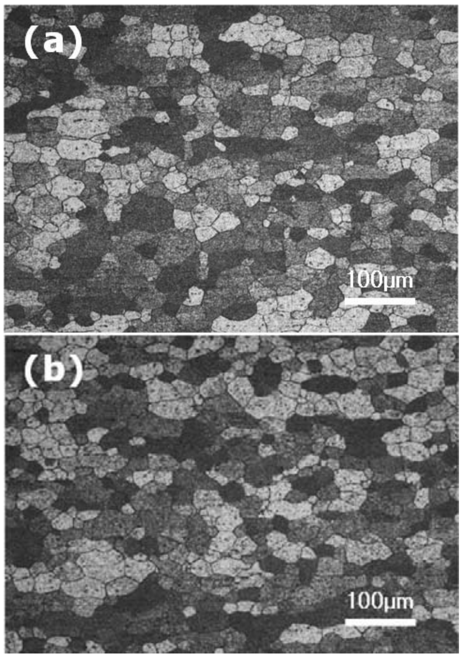


Fig. 3. Optical microscope (OM) images of sample surface: microstructures of (a) 1.58 mm Al sheet surface and (b) chemically etched 0.72 mm Al sheet surface.

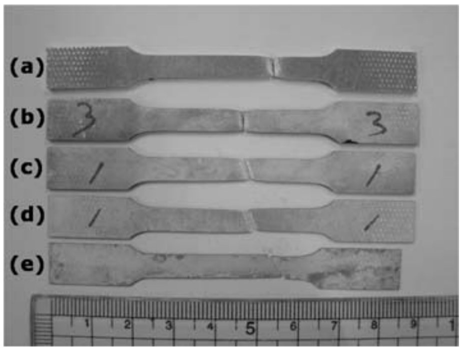


Fig. 4. Failure patterns of specimens from tensile test; (a) 1.58 mm-thick specimen, (b) 1.40 mm-thick specimen, (c) 1.04 mm-thick specimen, (d) 0.72 mm-thick specimen, and (e) 0.40 mm-thick specimen.

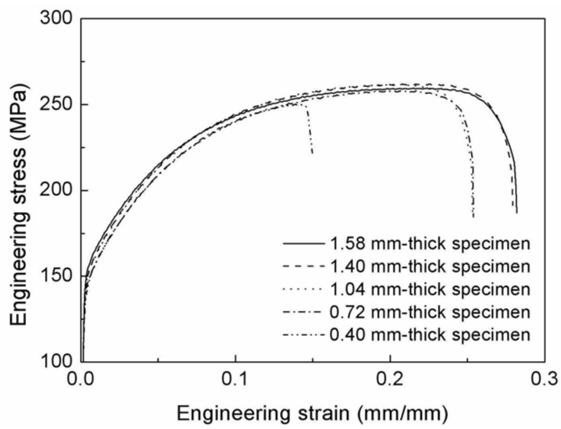
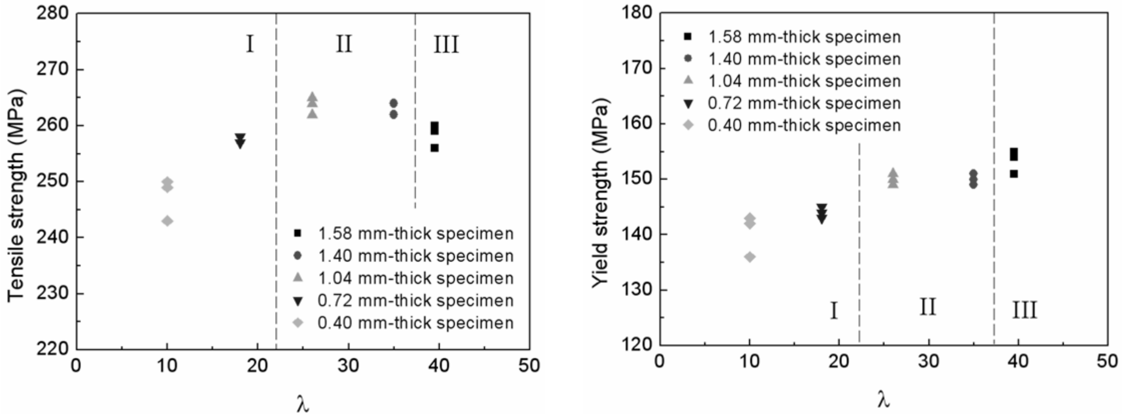
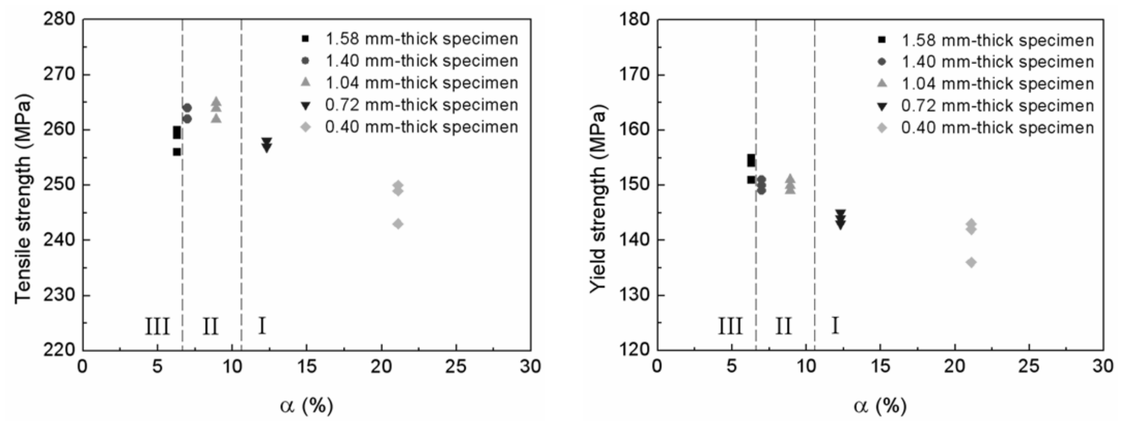


Fig. 5. Experimental engineering stress vs. engineering strain curves when reducing thickness.



(a) (b)

Fig. 6. Variation of (a) tensile and (b) yield strength with λ (ratio of thickness divided by grain size). The three thickness components represent the changed strength (I), the invariable strength (II), and the as-received strength (III) respectively.



(a) (b)

Fig. 7. Distribution of (a) tensile and (b) yield strength with variable α (volume fraction of grains with free surface). The three thickness components represent the changed strength (I), invariable strength (II), and as-received strength (III) respectively.

that the mechanical properties had been affected. The strength change according to λ is plotted in Fig. 6. The characteristics of areas I, II and III are summarized for the case of the same grain size and chemical etching. Whereas the strength decreased with the reduction of λ in area I, there was no change of strength according to λ in area II. The rolled surface affected the strength of the specimens in area III. Fig. 7 shows the relationship between the strength and α, where α changed with reduced thickness. And whereas the strength decreased with an increase of α in area I, there was no change of strength according to α in area II.

In this study, it was found that when there was no change of grain size, λ and α exhibited a relatively linear relation to a change of thickness in area I. In this area, a relative increase of free surface grains led to a decrease in the yield and tensile strengths, as the behavior of the grains located on the free surface became more and more dominant. In other words, dislocation was eliminated on the surface, the surface grains showing a lesser restraint force when compared with the inner grains, rendering the surface grains less resistant to deformation. As a result, the strength decreased. Moreover, the grain boundaries act as barriers to dislocations, relative increases of grain boundaries leading, correspondingly, to enhanced strength. These results are consistent with those of Raulea et al. [4]. Meanwhile, in area II, there was no change of strength when thickness was reduced. That is to say, in area II, the surface grains did not affect the mechanical properties. Further, it was noted that the strength began to decrease at the thickness of 1 mm (λ = 26, α =8.9), indicating that the effect of size was manifested only below the 1 mm thickness. It was expected that the specimens would have similar surface roughnesses after chemical etching in areas I and II; also, in area I, it was very difficult to distinguish the exact quantitative differences between the effect of grain size and the effect of surface roughness. Therefore, the effect only of surface roughness will be discussed in the next paragraph. In area III, the mechanical

Table 2. Variation of ductility parameters when reducing thickness.

Thickness (mm)	e_t (%)	e_u (%)	e_n (%)
1.58	29	20	9
1.40	29	20	9
1.04	26	20	6
0.72	26	20	6
0.40	15	14	1

properties of the rolled surface showed themselves to be different from those of the etched surface.

Next, the elongation was measured for the purpose of determining the effect of size on ductility. The ductility parameters measured in the tensile test are listed in Table 2. Uniform elongation (e_u) was defined as the onset of global necking, and necking strain (e_n) was defined as the elongation that proceeds from uniform elongation to a final fracture. Total elongation (e_t), then, was established as the sum of uniform elongation and necking strain. For all of the specimen thicknesses excepting 0.40 mm, the uniform elongation was 20%, and the necking strain decreased with smaller thicknesses.

It is already known that with smaller thicknesses, the fracture aspect changes from ductile fracture to shear fracture. For thicker specimens, necking in the direction of the thickness, called dimpled localized necking, occurs after uniform elongation. Additionally, as the plastically deformed zone widens, the necking strain increases. Meanwhile, for thinner specimens, plastic deformation is not diffuse but rather is concentrated in a cross-diagonal localized necking zone, which necking rapidly develops into shear fracture. As such, almost no necking strain is measured [16]. The present study derived similar results: a ductile fracture aspect appeared in the 1.58 mm-thick specimen, whereas the 0.72 mm-thick specimen showed both dimple-shaped necking and diagonal localized necking. The specimens of a thickness below 0.72 mm exhibited shear fracture, and in the case of the 0.4 mm-thick specimen, a typical shear fracture aspect appeared. Almost no necking strain appeared, and correspondingly, the uniform elongation decreased. In the very thin specimens, surface defects including roughness and inclusions promoted crack initiation points, and uniform elongation decreased.

3.2 Effect of surface roughness

The effect of surface roughness essentially has been ignored until now, as it impacts only within the micron range and in a very small area. However, this effect is becoming more important as more parts and materials are being miniaturized. Chemical etching has advantages, as microstructures are not altered, and no residual stress is generated, allowing investigation of just the effect of size. FEM also has merits, as it allows investigation of just the effect of surface roughness on mechanical properties.

Table 3. Variation of surface roughness when reducing thickness.

Thickness (mm)	Rolling direction		Transverse direction	
	Ra (μm)	Rz (μm)	Ra (μm)	Rz (μm)
1.58	0.105	0.886	0.236	1.182
1.40	0.837	4.248	0.924	5.491
1.04	0.665	3.572	0.991	7.758
0.40	0.764	6.124	0.979	6.660

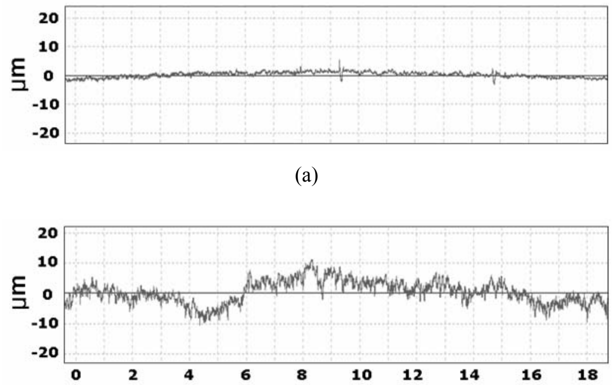


Fig. 8. Variation of surface roughness between (a) 1.58 mm-thick specimen and (b) 1.04 mm-thick specimen.

In the present study, FE models with and without periodic surface roughness were generated to reflect the real surface roughness and enable, thereby, study of the effect of surface roughness on mechanical properties. The surface roughness was measured for specimen thicknesses of 1.58 mm, 1.40 mm, 1.04 mm, and 0.40 mm, and the results are shown in Table 3. The rolling direction of the 1.58 mm-thick specimen showed lower roughness values than the transverse direction, and the rolled surface had lower roughness values than the chemically etched surface. The roughness values after the chemical etching were almost the same, and the roughness values (Rz) were about 3 ~ 7 μm. The surface roughness measured for the rolled specimens and chemically etched specimens are shown in Fig. 8. As can be seen, the surface roughness of the chemically etched specimens was higher than that of the rolled specimens, and fluctuated within a 0 ~ 10 μm range, the maximum peak-to-valley range being about 20 μm.

Finite element (FE) models were derived according to the measured surface roughness, and for simplicity, a periodic surface roughness measure was introduced. The surface roughness effected had a depth of 10 μm and a pitch of 100 μm. The threshold value C, indicating the initiation of ductile fracture, was calculated as 0.4 in a tensile test.

The FEM results are shown in Fig. 9, and a comparison of these results with the engineering stress-strains uncovered in the experiments is shown in Fig. 10. The FEM results accurately reflect the ductile fractures revealed in the experiments,

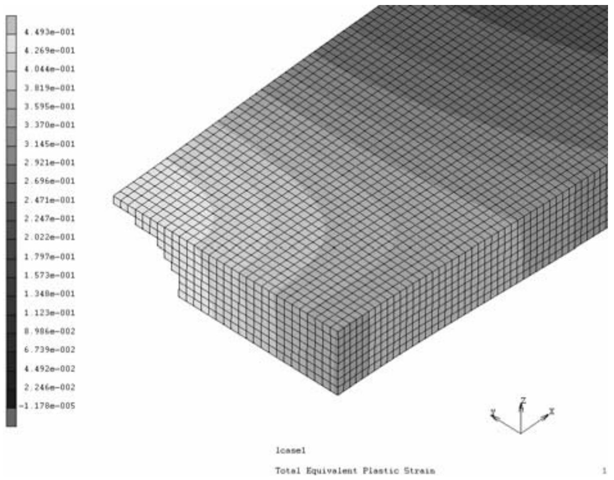


Fig. 9. Result of FE simulation in case of 1.58 mm-thick specimen with flattened surface and elimination of meshes when ductile fracture criteria in center of specimen reached.

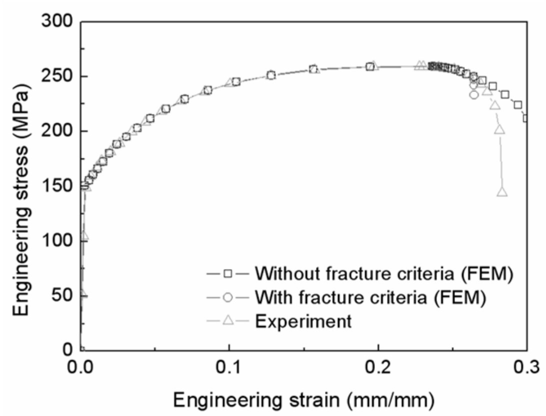


Fig. 10. Comparison of experimental and FEM engineering stress-strain curves for 1.58 mm-thick specimen with flattened surface.

the cracks having initiated at the center of the cross-section of the gauge length. The engineering stress-strain curve behavior from the experiments, and the corresponding FEM results, were almost the same, though there was some difference near the fracture area. In the FEM results, the fracture onset point was not shown clearly when the ductile fracture condition was not applied. However, under that condition, the fracture point was, in fact, clearly evident. The difference, near the fracture, between the experimental stress-strain curves and the FEM results was owed to the difficulty of directly measuring the thickness there.

The effect of the surface roughness on the stress-strain curves in the case of the 1.58 mm- and 0.40 mm-thick specimens is illustrated in Fig. 11. Whereas with no surface roughness (i.e. the flattened surface) the tensile strength, 259 MPa, was the same, with periodic surface roughness it was lower, 258 MPa for 1.58 mm-thick specimen, and 253 MPa for the 0.4 mm-thick specimen. That is to say, the tensile strength of the 1.58 mm-thick specimen with periodic surface roughness was lower than that of the flattened-surface specimen by

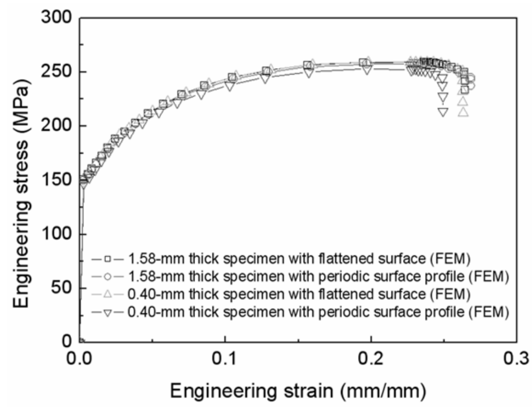


Fig. 11. Comparison of FEM engineering stress-strain curves for different surface roughnesses.

1MPa, and the tensile strength of the 0.4 mm-thick specimen with periodic surface roughness was lower by 6MPa. Moreover, it was found that the stress-strain curve decreased with decreasing specimen thickness for the same surface roughness. Therefore, it can be assumed that the effect of surface roughness on the stress-strain curve will increase with decreasing specimen thickness for the same surface roughness. Notably, the tensile strength drop in the tensile test was three times larger than in the simulation. In other words, the surface roughness effect on the tensile strength was 1/3 of the total strength drop, and the size effect was 2/3. However, it was difficult to precisely predict the effect of surface roughness in the simulation, because we assumed that the specimens had periodic surface roughness. Nonetheless, we found that the surface roughness does affect the stress-strain curve.

Similarly to the tensile strength, the elongation was almost the same when the specimens had no surface roughness, 0.264 mm/mm for the 1.58 mm specimen and 0.263 mm/mm for the 0.4 mm specimen, and yet lower when there was surface roughness, 0.268 mm/mm for the 1.58 mm specimen and 0.249 mm/mm for the 0.4 mm specimen. Accordingly, the stress-strain curves and fracture strains for the 1.58 mm and 0.40 mm specimens, with no surface roughness, were almost same. However, the surface roughness decreased the stress-strain curves and fracture strains, and the effect of the surface roughness increased as the thickness was reduced. Whereas the effect of the surface roughness on the stress-strain curve shape and elongation was minimal in the case of the 1.58 mm specimen, it increased for the 0.4 mm specimen. This reflected the fact that the effect of the surface roughness increased for reduced thicknesses and the same surface roughness. The surface roughness valleys signify the thickness reductions, and the stress is concentrated in the valleys. Thereby the fracture strain was effected.

The FEM and experimental results for the 0.4 mm specimen are compared, in Fig. 12, for total elongations of 0.249 mm/mm (FEM) and 0.147 mm/mm (in the experiment), respectively. It is apparent that the ductile fracture model used in the FEM is not suitable for predicting the elongation of a thin

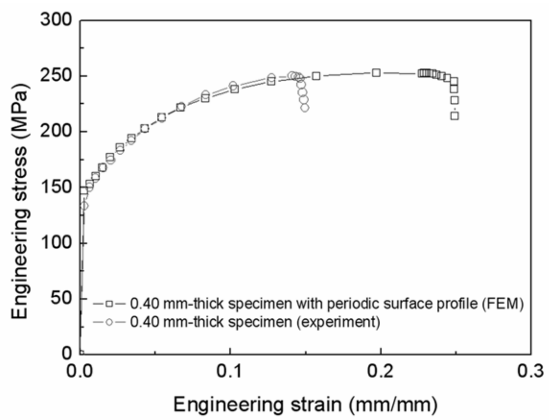


Fig. 12. Comparison of experimental and FEM engineering stress-strain curves for 0.40 mm-thick specimen.

specimen and that, therefore, improved accuracy requires that a new fracture model be adopted.

It is very difficult to simulate a real surface roughness in an FE model, which explains the difference in the FEM results in this study. Thus, in the future, a fractal method [17] will be adopted to produce a real surface suitable for the study of the effect of surface roughness on mechanical properties of aluminum sheets.

4. Conclusions

This study investigated the effect of size on the mechanical properties of aluminum 6K21-T4 sheets when using chemical etching to reduce specimen thicknesses. The results were as follows.

(1) Chemical etching, as compared with rolling and heat treatment methods, is an effective method for studying the effect of grain size.

(2) The mechanical properties changed while the thickness was reduced and the microstructure and grain size were maintained. The tensile and yield strengths decreased when the thickness was reduced below a critical thickness of 1 mm (λ = 26, α = 8.9). An almost linear relationship was shown between strength and thickness reduction. Meanwhile, the necking strain decreased when the material was miniaturized, and uniform elongation decreased when the thickness was reduced.

(3) When matching the engineering stress-strain curves obtained from the FEM with the experimental results, the elongation was well predicted by the modified Cockroft-Latham equation, one of the ductile fracture criteria. The effects of size and surface roughness increased as the thickness was reduced, and the ductile fracture model was found to be unsuitable for prediction of the elongation of shear-fractured specimens.

(4) The effects of size and surface roughness on the mechanical properties must be considered when materials and parts are miniaturized.

(5) In the future, a 3-dimensional fractal model will be considered for study of the effect of real surface roughness [17].

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