ANISOTROPY OF BULK-FORMABILITY IN 2024-T351 ALUMINUM PLATES AND BARS

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ABSTRACT

Anisotropy of bulk-formability in 2024-T351 Al-alloy plates and square bars is determined using the forming limit line technique developed for the analysis of workability in bulk-deformation processes. To this end, upset tests were performed in the longitudinal, long transverse, and short transverse directions in plates, and in the longitudinal, circumferential, and radial directions in square bars. In the longitudinal direction, forming limit lines were obtained from bend tests in both geometries.

In both plates and bars, the workability level is found to be approximately 50% higher when tensile stresses are parallel to inclusion plane and elongation (longitudinal bend tests) than when they are perpendicular to the plane of inclusions (longitudinal and long transverse upset tests in plates and longitudinal and circumferential upset tests in bars). The degree of anisotropy in the aluminum alloy is comparable to that of previously determined hot-rolled AISI 1045 steel plates and AISI 1040 round steel bars, even though the aluminum alloy exhibits localization of flow during deformation. It is concluded that mechanical anisotropy is not suppressed by the occurrence of shear localization.

KEYWORDS

Workability, bulk-formability, deformation processes, forming limit lines, ductile fracture, mechanical anisotropy, aluminum alloys, shear localization, upset tests.

INTRODUCTION

Free surface fractures are the most common type of fracture in bulk-deformation processes, generally determining the limits of deformation that can be imparted to the deforming material. Such fractures occur at the free surfaces of the workpiece during processing, e.g., edge cracking in rolling, cracking of free surfaces of a preform in an open-die forging or before contact is achieved between the preform and die walls during a closed-die forging.

A fracture criterion based on limiting strains-to-fracture has been developed by Kuhn, Lee, and Ertürk (1973) for the prediction and prevention of surface cracks in bulk-deformation processes. Local strains, calculated from measurements of grid markings at the fracture sites on the free surfaces of cylinders upset under different friction conditions and with varying height-to-diameter ratios, are plotted. These strains, varying over a wide range, establish a fracture line with a slope of -1/2. Properly aligned with respect to inclusion alignment, bend tests give fracture strains falling onto the extension of the fracture line determined from upset tests, also with a slope of -1/2. However, bend fracture data encompass a narrower strain range and the measured strains are smaller in magnitude. Spread in the bend data is obtained by using specimens with varying width-to-thickness ratios.

The height (or intercept) of the fracture line obtained from upset or bend tests, or both, is independent of process variables and is a material property. The region of allowable states of strain (safe region) is enlarged as the height of the forming limit line increases. This allows the use of the intercept as an index of workability of the material under consideration; with this approach, the effect of material variables on bulk-formability can be evaluated (Ertürk, 1979; Ertürk and Kazazoğlu, 1980).

Mechanical fibering of fracture nuclei during previous working affects the bulk-forming limits in a wrought material that will be subjected to further shaping. In a material having a degree of alignment of inclusions, tensile stresses interact with aligned inclusions, leading to anisotropy in properties related to the fracture behavior of the material. (The term inclusion is used in the general sense, to denote all types of ductile fracture nuclei such as weak interfaces, pores, chemically segregated areas, second phase particles, foreign inclusions, etc.)

Ertürk, Otto, and Kuhn (1974), with complimentary results by Suh and Kuhn (1975), have shown that three levels of workability exist in hot-rolled AISI 1045 steel plates. Highest workability is obtained when the critical tensile stresses are parallel to the inclusion plane and elongation (bend tests in the rolling direction). (Upset tests cannot generate critical tensile stresses and the workability level cannot be determined through these tests in the longitudinal direction. Since bend tests can generate critical tensile stresses in the direction of working, it is necessary to use bend tests to determine the workability level in this orientation.) When the critical tensile stresses are perpendicular to the plane of inclusions (longitudinal and long transverse upset tests), workability is at the lowest level. In the long transverse direction (short transverse upset tests), the tensile stresses are parallel to the inclusion plane but perpendicular to inclusion elongation, and workability is at an intermediate level. Approximately 50% improvement is obtained by aligning the critical tensile stresses parallel to the inclusion plane and elongation. A similar degree of anisotropy (∿ 65%) has been obtained for hot-rolled AISI 1040 round steel bars (Ertürk, 1980), in which inclusion alignment is symmetrical with respect to the axis of the bar, in contrast to plates where the mid-plane of the plate provides the symmetry plane.

These previous analyses of the effect of mechanical fibering on bulk-formability have concentrated on steels. The present study extends the earlier works to a non-ferrous material, evaluating the degree of anisotropy of bulk-formability in 2024-T351 Al-alloy plates and square bars. Aluminum alloys commonly exhibit localization of flow within narrow zones during deformation (Chung and co-workers, 1977; Leroy and Embury, 1978), impairing their ductile capacity. It has recently been shown (Ertürk and Kazazoğlu, 1980) that workability levels of 2000 and 7000 series Al-alloys are affected by flow localization; their workability levels are found to be as low as 1/2 that of carbon steels (Ertürk, 1979). In a material exhibiting localization of shear, flow localization might interfere with the interaction of tensile stresses with aligned inclusions, suppressing the mechanical anisotropy effects in the material. Therefore, the purpose of the present analysis is to determine the degree of anisotropy in 2024-T351 aluminum plateş and bars, and thereby assess the role of shear localization in mechanical anisotropy.

EXPERIMENTAL PROCEDURE

Material

Commercially available 2024-T351 Al-alloy was obtained in two geometries: i) 50.8 mm wide and 12.7 mm thick plate, and ii) 50.8 mm square bar. The chemical compositions are given in Table 1.

TABLE 1 Chemical Compositions of 2024-T351 Aluminum

2024-T351 Al-alloy	Si%	Cu%	Mn%	Mg%	Zn%	Fe%
Plate	0.11	4.20	0.60	1.10	0.20	0.42
Square bar	----	4.08	0.71	1.20	----	0.50

Composite micrographs showing the microstructure of the alloys are presented in Fig. 1. Grains are highly elongated, and precipitated and undissolving particle stringers are aligned in the direction of working. The heavily banded structure results in oval-shaped grains and particles in the cross-section perpendicular to the direction of working.

Testing

Upset cylinders, 12 mm in diameter, were cut with their axes coinciding with the three principal orientations in the rectangular geometry (plate): longitudinal (L), long transverse (T), and short transverse (S), depicted in Fig. 2(a). Bend tests were only performed in the longitudinal direction (Ertürk, 1980), Fig. 2(a). Uniaxial tension test specimens were fabricated in the longitudinal and long transverse directions only, Fig. 2(a); due to the limited thickness of the plate, it was not feasible to manufacture tension specimens in the thickness direction in this geometry.

In the square bar geometry, the principal orientations (analogous to circular geometry) are: longitudinal (L), circumferential (C), and radial (R). Upset and tension test specimens were machined in these directions, and bend tests were again performed in the longitudinal direction only, Fig. 2(b). For both geometries, the critical tensile stresses developed in each specimen during testing are indicated by double arrows in Fig. 2.

The upset cylinders were compressed between two parallel platens in a Universal Testing Machine at a crosshead speed of 20 mm/min. The limiting strains were calculated from diameter measurements (ε_θ) and from measurements of the separation of two lines, 1.2 mm apart, scribed at the equatorial region of the cylinders by means of a carbide-tipped height gage ($-\varepsilon_z$). These measurements were made at the first detection of a crack by the unaided eye. A micrometer was used for diameter

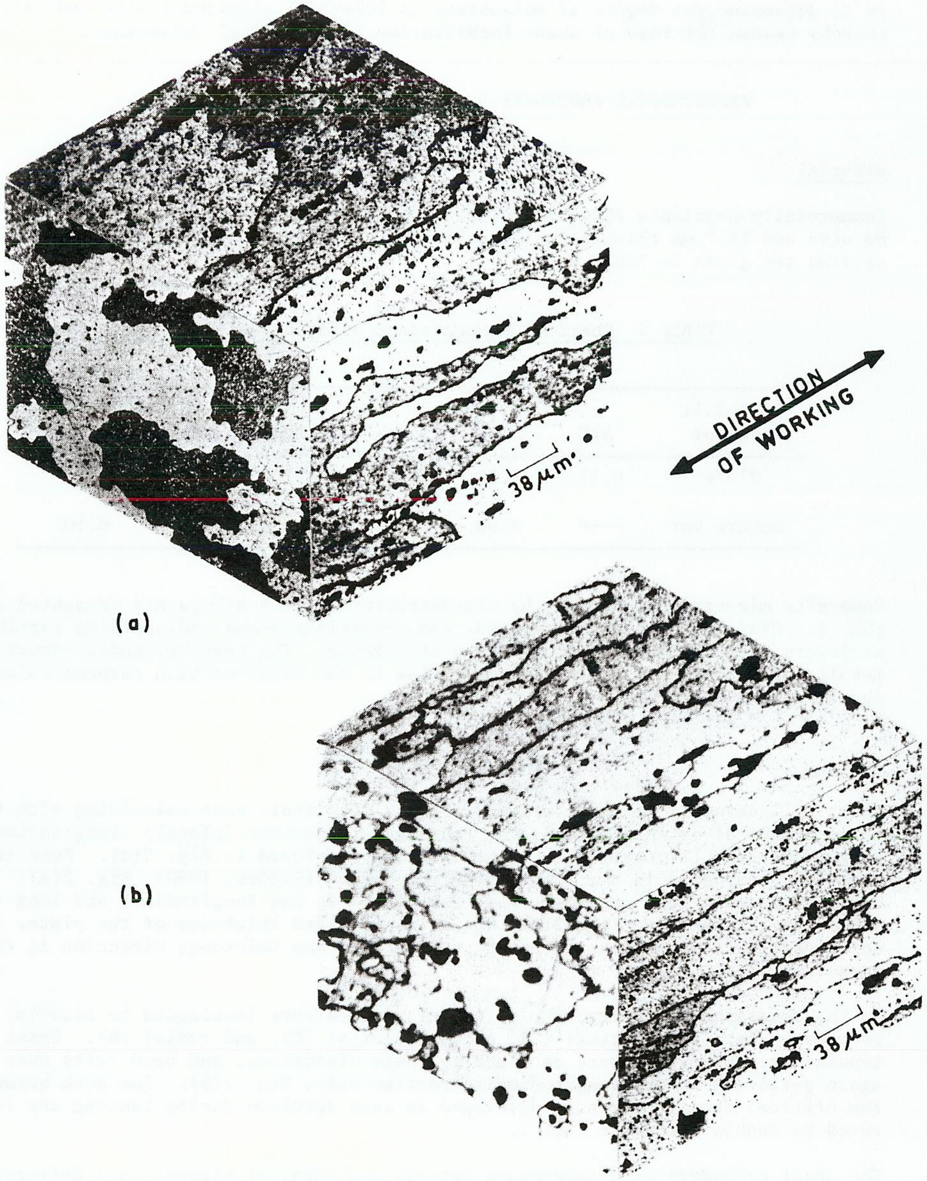


Fig. 1. Composite micrographs showing mechanical fibering of grains and particles in 2024-T351 aluminum (a) plates and (b) square bars.

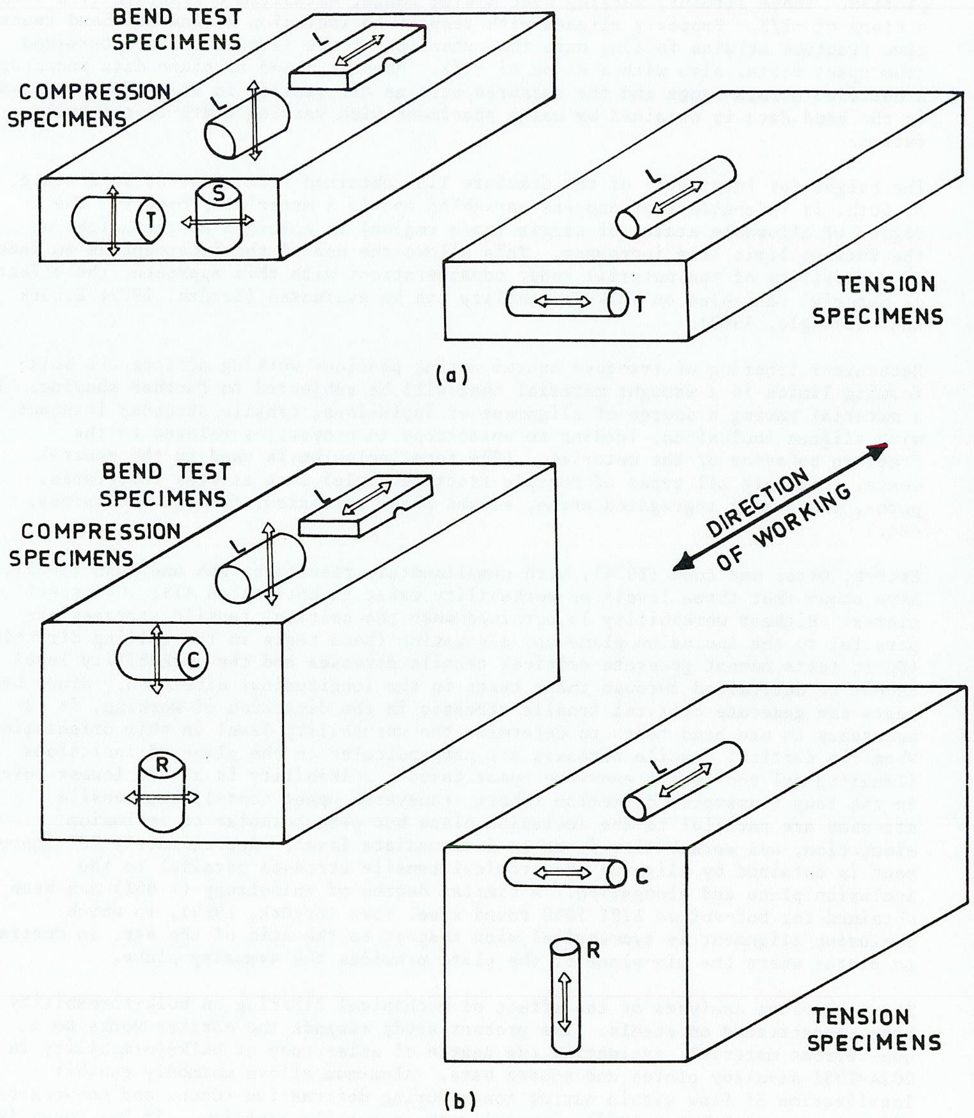


Fig. 2. Orientations of upset, bend, and tension test specimens in (a) rectangular plate and (b) square bar geometries.

measurements, and a precision measuring microscope, with an accuracy of ± 0.001 mm, was used for line separation measurements.

Upset test specimens were manufactured from the plate stock with a height-to-diameter (aspect) ratio of 1.0. A spread in the upset fracture data for plates was obtained by varying the friction condition at the die-contact surface, using knurled, polished, and polished and lubricated (with MoS_2 in grease) dies. In bars, only polished dies were used, and spread in the upset fracture data was achieved by varying the aspect ratio of the specimens between 0.5 and 1.25.

Longitudinal upset specimens cut from the square bar exhibited out-of-roundness during testing. This made measurement of the circumferential strain difficult; the average of minor and major diameters was used. In a few specimens, fracture strains were measured from square grid marks stamped onto the surface of cylinders. The limiting strains thus obtained agreed with those obtained using averages of diameters.

Bend test specimens were grooved as shown in Fig. 2 (Suh and Kuhn, 1975; Ertürk, 1980), and the tests were carried out using a bend apparatus on a Universal Testing Machine operating at a crosshead speed of 20 mm/min. Fracture strains were measured from separations of a 1.2 mm square grid stamped onto the outer surfaces. A precision measuring microscope was used for the line separation measurements. Spread in the bend fracture data was obtained by changing the width-to-thickness ratio of the rectangular specimens between 1 and 8.

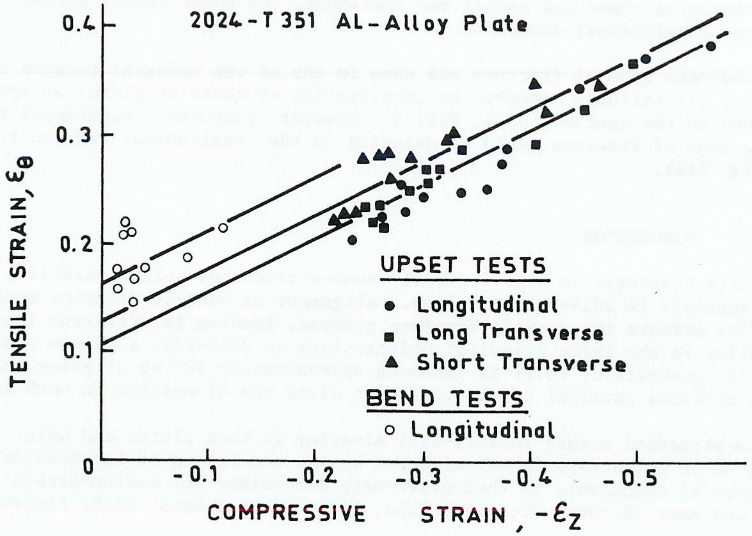
Tension test specimens, 6.35 mm in diameter and 24.5 mm in gage length, were tested in a Universal Testing Machine at a crosshead speed of 20 mm/min. Engineering stress-strain curves and tensile properties of the alloys in the principal orientations in both geometries are given in the appendix.

RESULTS

Forming limit lines corresponding to the three principal orientations in 2024-T351 Al-alloy plates and bars are given in Fig. 3. Alignment of ductile fracture nuclei during processing leads to three different levels of workability in both geometries. Workability is highest in the longitudinal direction, where critical tensile stresses (in the bend tests) are parallel to the inclusion plane and elongation. Lowest workability is obtained from upset tests in which the critical tensile stresses are perpendicular to the inclusion plane (longitudinal and long transverse upset specimens in plates, and longitudinal and circumferential upset cylinders in square bars, Fig. 2). The critical secondary tensile stresses generated in the short transverse upset cylinders in plates and radial specimens in bars are parallel to the plane of inclusions, though perpendicular to the direction of inclusion elongation, leading to an intermediate level of workability.

Statistical curve fitting techniques revealed that workability indices of the plate and bar stock were almost identical in each principal direction. The index of workability is 0.11 in the lowest workability orientation: short transverse in plate and radial direction in bar. In the long transverse direction in plate and circumferential orientation in bar, the workability index is 0.13. The level of workability in the longitudinal direction is 0.16 in plate and 0.165 in square bar.

The upset specimens gave exclusively 45 degree cracks (also referred to as shear cracks) in all directions in both geometries. In the longitudinal, long transverse, and circumferential directions, these shear cracks occurred at the ends of diameters parallel to the inclusion plane, 180° apart in all specimens. In the



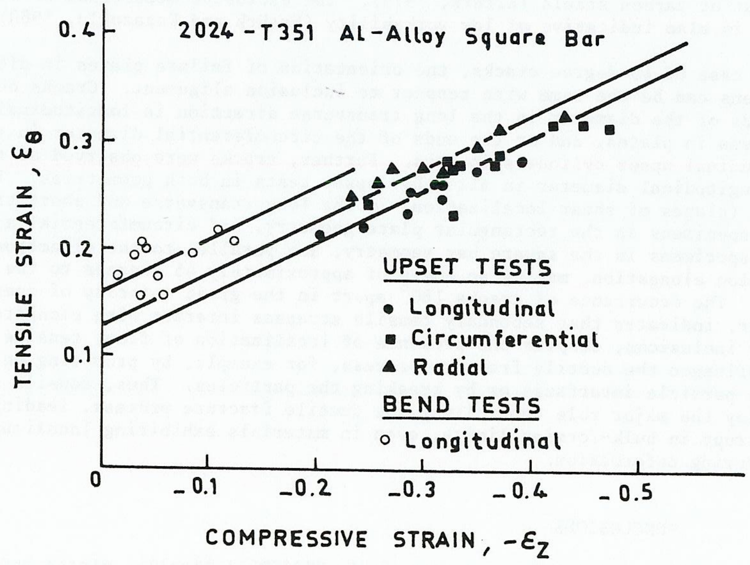


Fig. 3. Forming limit lines corresponding to the three principal orientations in 2024-T351 aluminum plates and square bars.

short transverse plate and radial bar specimens, the shear cracks spread ± 20° around the longitudinal diameters.

No cup-and-cone type of fracture was seen in any of the uniaxial tension test specimens; all failures occurred by localization of shear on planes at approximately 45 degrees to the specimen axis, Fig. 4. However, features transitional to cup-and-cone type of fracture could be detected in the longitudinal tension tests in bars, Fig. 4(b).

DISCUSSION

The results presented in Fig. 3 clearly demonstrate that bulk-formability limits are anisotropic in 2024-T351 Al-alloy. Alignment of ductile fracture nuclei during processing affects the ductile fracture process, leading to different levels of workability in the three principal orientations in 2024-T351 aluminum plates and bars. The workability level is improved approximately 50% by aligning the critical tensile stresses parallel to the inclusion plane and elongation in both geometries.

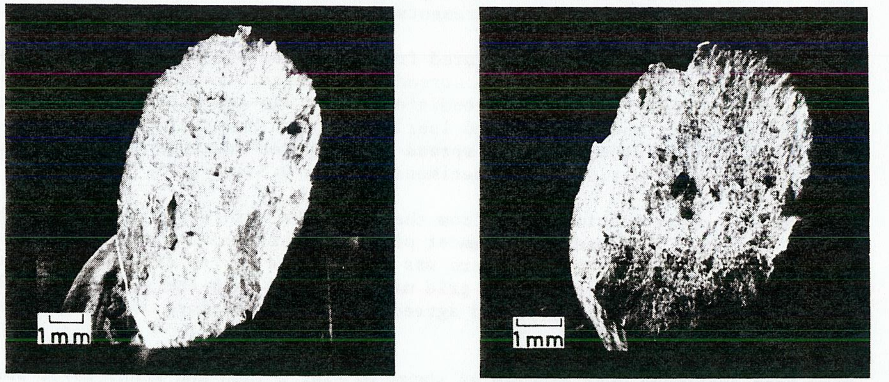
Shear localization occurs in 2024-T351 Al-alloy in both plates and bars. However, the degree of anisotropy is not affected by the occurrence of localization of flow; the degree is comparable to that previously determined for medium carbon steel plates and bars (Ertürk, Otto, and Kuhn, 1974; Suh and Kuhn, 1975; Ertürk, 1980).

Ertürk and Kazazoğlu (1980) have shown that susceptibility to shear localization gives lower levels of workability in heat-treatable aluminum alloys (2000 and 7000 series). The results of the present study are in conformity with the earlier findings; the workability level of 2024-T351 Al-alloy is of the same order as 2024 Al-alloy in the solution treated and peak aged conditions, and approximately 1/2 that of carbon steels (Ertürk, 1979). The exclusive occurrence of 45 degree cracks is also indicative of low workability (Ertürk and Kazazoğlu, 1980).

In the case of 45 degree cracks, the orientation of failure planes in different specimens can be the same with respect to inclusion alignment. Cracks occurred at the ends of the diameter in the long transverse direction in longitudinal upset specimens in plates, and at the ends of the circumferential diameter in the longitudinal upset cylinders in bars. Further, cracks were observed at the ends of the longitudinal diameter in all other upset tests in both geometries. The failure planes (planes of shear localization) in the long transverse and short transverse upset specimens in the rectangular plate geometry, and circumferential and radial upset specimens in the square bar geometry, are parallel to the direction of inclusion elongation, making an angle of approximately 45 degrees to the inclusion plane. The occurrence of cracks 180° apart in the great majority of specimens, however, indicates that secondary tensile stresses interact with elongated and spread inclusions, despite the presence of localization of flow; tensile stresses can influence the ductile fracture process, for example, by promoting decohesion at the particle interfaces or by breaking the particles. Thus, tensile stresses can play the major role controlling the ductile fracture process, leading to anisotropy in bulk-forming limits, even in materials exhibiting localization of flow during deformation.

CONCLUSIONS

Bulk-formability limits are anisotropic in 2024-T351 Al-alloy plates and square bars. Three levels of workability exist, corresponding to the three principal directions in plates and bars. The workability index is approximately 50% higher when critical tensile stresses are aligned parallel to inclusion plane and elongation than when they are perpendicular to the inclusion plane. This degree of anisotropy is comparable to that of previously determined medium carbon steel plates and round bars. It is concluded that the occurrence of shear localization during deformation does not suppress mechanical anisotropy effects in 2024-T351 Al-alloy.



(a) (b)

Fig. 4. Localized shear failure in tension tests in 2024-T351 aluminum in (a) longitudinal direction - plate, and (b) longitudinal direction - bar.

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APPENDIX

TABLE A1. Tensile Properties of 2024-T351 Aluminum Plates and Bars in Different Orientations[†]

Material	Orientation	0.2% Yield Strength MPa	Tensile Strength MPa	n	Elongation (%)		Reduction in Area (%)
					Uniform	Total	
2024-T351 Plate	Longitudinal	361	489	0.26	17.5	19.5	25.0
	Long Transverse	329	474	0.31	17.6	19.2	20.9
2024-T351 Square Bar	Longitudinal	335	458	0.31	19.8	24.0	25.4
	Circumferential	315	450	0.32	--	16.3	21.2
	Radial	301	425	0.31	--	13.0	17.9

[†] Average of six tests in each orientation.

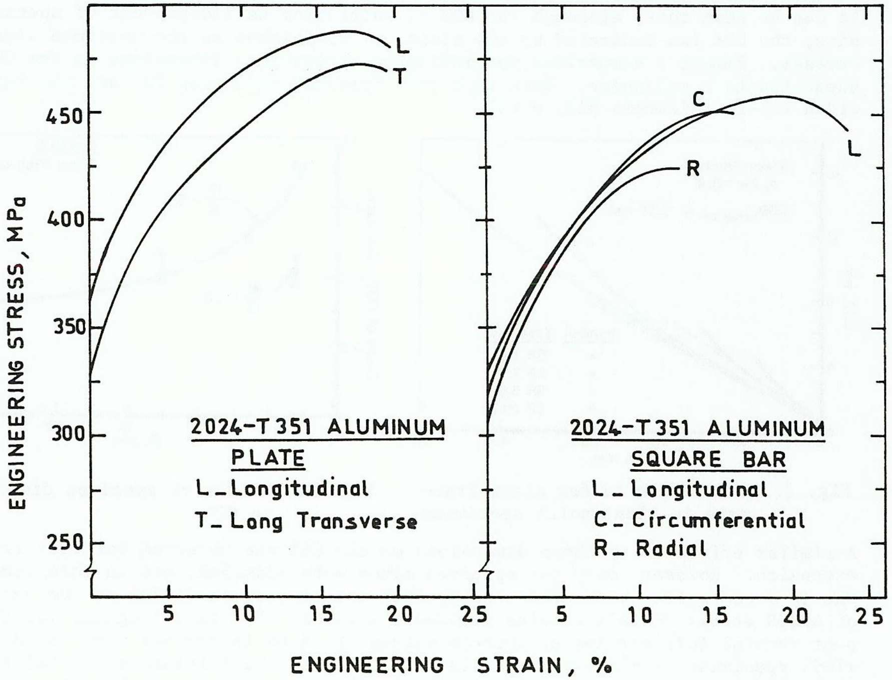

Fig. A1. Engineering stress-strain curves for 2024-T351 aluminum plates and square bars in different orientations.