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**NATIONAL AERONAUTICS AND SPACE ADMINISTRATION**

Texture Strengthening and Fracture Toughness of 4Al-0.2 O and 5Al-2.5Sn ELI  
Titanium Sheet Biaxial Stress Fields at Room and Cryogenic Temperatures

By Timothy L. Sullivan<sup>1</sup>

Abstract

Burst tests of six-inch diameter cylindrical pressure vessels (1 to 2 stress field) fabricated from nominally 0.020 inch thick material showed significant increases in strength over uniaxial values. Biaxial yield strengths as high as 1.53 times uniaxial yield were obtained. The Ti-4Al-0.2 O alloy with a room temperature plastic Poisson's ratio of 0.845 ( $R = 5.45$ ) generally had greater biaxial yield, ultimate, and weld strength at a given temperature than did the Ti-5Al-2.5Sn ELI alloy (room temperature plastic Poisson's ratio equals 0.732;  $R = 2.73$ ). However, tests of cracked cylinders at -320 and -423 F showed the Ti-5Al-2.5Sn ELI alloy had less notch sensitivity for through-the-thickness cracks 0.1 inch or longer. Plastic Poisson's ratio obtained from a uniaxial tension test was used to predict the amount of biaxial strengthening.

Key Words

Texture strengthening, texture hardening, texturing, fracture toughness uniaxial stress, biaxial stress, 1 to 2 stress field, sheet, titanium alloys, Ti-4Al-0.2 O, Ti-5Al-2.5Sn ELI, pressure vessel, notches, yield strength, ultimate strength, weld strength, plastic Poisson's ratio, room temperature, cryogenic temperature, -320 F, -423 F.

## Introduction

Anisotropy in certain sheet materials can cause appreciable strengthening under conditions of biaxial stress. Whereas yielding in a 1 to 2 stress field is predicted to occur at 1.15 times the uniaxial yield strength for the isotropic case, it is predicted to occur at 1.5 times or greater for certain anisotropy (1). The form of anisotropy referred to is called texturing and is characterized by isotropy in the plane of the sheet with considerable anisotropy normal to the sheet plane. Conventionally, texturing is quantitatively characterized by a strain-ratio parameter,  $R$ , which is the ratio of width strain to thickness strain measured on a uniaxial tension specimen. Uniaxial studies of texturing in titanium alloys have been made by several investigators (2 - 5). Sliney et al (6) and Babel et al (7) have experimentally investigated the biaxial strengthening of Ti-5Al-2.5Sn at room temperature.

In alpha titanium alloys maximum strengthening occurs when the basal (0001) planes of the hexagonal close-packed crystals are parallel to the plane of the sheet (Fig. 1). In unalloyed titanium sheet the basal planes are found to be inclined approximately  $30^\circ$  toward the transverse direction. However, certain alloying agents (i.e., alpha stabilizers) inhibit rotation of these planes and the addition of 3.8 percent aluminum (Ti-4Al) is reported to give close to the ideal texture after rolling (4). Because of the potential usefulness of this alloy as a cryogenic propellant tank material, a program was undertaken at the Lewis Research Center to determine the strength and fracture toughness of 0.020 inch thick Ti-4Al-0.2 O sheet in both uniaxial and 1 to 2 biaxial stress fields. A parallel study was conducted with the extra-low-interstitial (ELI) grade of a less textured

titanium alloy, Ti-5Al-2.5Sn. Results for each are compared. In addition the weld strengths of a limited number of uniaxial and biaxial test specimens were determined.

Uniaxial smooth and notch properties for both alloys were determined at room temperature, -320 and -423 F. Smooth biaxial properties were determined from burst tests of 6-inch diameter cylindrical pressure vessels over the same range of test temperatures. Notched pressure vessel tests were made at -320 and -423 F. An attempt is made to characterize by plastic Poisson's ratio the amount of texturing in the two alloys.

#### Analytical Basis for Texture Strengthening

By applying Hill's theory for the yielding of anisotropic sheet materials (8), Backofen et al (1) indicate that for the case of rotational symmetry about the thickness direction (isotropy in the plane of the sheet) the yield criterion becomes

$$\frac{\sigma_x}{\sigma_{ys}} = \left[ 1 + \alpha^2 - \alpha \frac{2R}{R+1} \right]^{-1/2} \quad (1)$$

where  $\alpha$  is the ratio of the principal stresses in the plane of the sheet  $\sigma_y/\sigma_x$ ,  $\sigma_{ys}$  is the uniaxial yield strength in the plane of the sheet and  $R$  is the ratio of plastic strain in the width direction of the sheet  $\epsilon_w$  to plastic strain in the thickness direction of the sheet  $\epsilon_t$ , these strains being determined from smooth uniaxial tension tests. It is assumed in Eq. (1) that the principal directions of anisotropy correspond with the principal directions of stress. The derivation of this equation is found in appendix A of (6).

Because of the difficulty in accurately measuring strain in the thickness direction of thin gage materials, it is desirable to base  $R$  on a

more easily measured quantity, i.e., strain in the length direction  $\epsilon_l$ . This can be done if constancy of volume is assumed. If yielding has occurred,  $\epsilon_l + \epsilon_w + \epsilon_t = 0$  for small strains. As a result,  $\epsilon_t$  can be written in terms of more easily measured quantities. Thus,

$$R = \frac{\epsilon_w}{\epsilon_t} = \frac{\epsilon_w}{-\epsilon_w - \epsilon_l} = \frac{\nu_p}{1 - \nu_p} \quad (2)$$

where  $\nu_p$  is the plastic Poisson's ratio,  $-\epsilon_w/\epsilon_l$ .

#### Experimental Apparatus and Procedure

Test specimens were fabricated from sheet nominally 0.020 inch thick produced from a single heat for each alloy. The mill analysis and annealing treatment provided by the supplier are given in Table 1.

Table 1 -- Annealing Treatment and Composition (Percent by Weight) for Alloys Investigated

Material	Heat no.	Anneal	C	Fe	N	Al	H	O	Sn	Mn
Ti-4Al-0.2 O	V-3002	1325 F for 4 hr furnace cooled	0.023	0.12	0.014	3.8	0.007-.010	0.21	--	--
Ti-5Al-2.5Sn ELI	D-3272	1325 F for 4 hr furnace cooled	0.022	0.08	0.014	5.1	0.006-.009	0.08	2.5	<0.006

#### Uniaxial Tests

The specimens used to determine the uniaxial properties of the sheet are shown in Fig. 2. Finished specimens were stress relieved according to the schedule outlined in the next section for biaxial test specimens. Conventional smooth properties including 0.2 percent offset yield strength and plastic Poisson's ratio were obtained using the specimen shown in Fig. 2(a). Weld specimens were of this type (Fig. 2(a)) and had their weld beads normal

to the loading axis. Weld beads were not ground flush with the parent metal so that they would model more closely the fabrication of component hardware. Notch strength (based upon initial crack length) and fracture toughness (based upon critical crack length) were determined using the specimen shown in Fig. 2(b). Cryogenic test temperatures were obtained by immersing the specimens in liquid nitrogen or liquid hydrogen.

The NASA continuity gage (9) was used to measure the slow crack growth which took place prior to catastrophic failure. At -423 F the transition between slow and rapid crack growth was abrupt and the critical crack length was readily obtainable from the gage output directly. At -320 F, however, the transition was gradual and a crack velocity of 0.1 inch per second was arbitrarily selected to define the critical crack length. Because the crack velocity selected is relatively slow, the critical crack lengths used to calculate fracture toughness were conservative.

Plastic Poisson's ratios were obtained using high-elongation copper-nickel foil strain gages on the test section of tensile specimens. One gage was mounted parallel to the direction of loading on one side of the specimen while a second gage was mounted transverse to the direction of loading on the other side of the specimen, directly behind the first gage. This allowed strain measurement in both directions at essentially the same location. Strain differences from one surface to the other due to bending would not be expected from the thin sheet used in this investigation. The output of the gages was used to drive an X-Y recorder. The specimen was loaded in tension until yielding had occurred. To restrict the strain ratio to purely plastic (nonrecoverable) strain components in accordance with the assumption of volume constancy, the load was then held constant as the strain continued to

increase until the end of the recorder chart travel was reached (about 2 percent strain). The slope of the curve of  $\epsilon_w$  versus  $\epsilon_l$  after yielding occurred was taken as the plastic Poisson's ratio. A typical record of  $\epsilon_w$  versus  $\epsilon_l$  is shown in Fig. 3.

#### Biaxial Tests

Six-inch diameter cylindrical pressure vessels 18 inches long were fabricated using a single longitudinal butt weld. The sheet was oriented so that the rolling direction of the material was normal to the weld. Welding was performed in an argon-inerted chamber with a tungsten electrode. No filler material was added. Following fabrication cylinders were stress relieved in vacuum and furnace cooled. The stress relief schedules were one hour at 1000 F for the Ti-4Al-0.2 O alloy and two hours at 1100 F for the Ti-5Al-2.5Sn ELI alloy.

Cracked cylinders were flawed by electrical discharge machining longitudinal slots through the cylinder wall followed by low stress fatiguing to obtain sharp cracks at the slot ends. An internal patch (10) was taped over the crack for pressurizing to failure.

To preclude weld failures in cylinders used to determine parent material biaxial yield and ultimate strengths, it was necessary to reinforce these welds. This was done by applying internal and external overlays of commercially pure titanium strip to the weld. The strips were 0.004 inch thick and approximately two inches wide. For room temperature tests, an epoxy-nylon adhesive was used to bond the strips to the cylinders. For tests and -320 and -423 F, a polyester adhesive was used. In lap shear tests this adhesive had shown good strength at cryogenic temperatures. End closure was obtained by embedding the cylinder ends in heads filled with a low-melting-



point alloy (10).

Strippable-backed nickel-chrome foil strain gages were applied to all uncracked cylinders using an epoxy adhesive for room temperature tests and the polyester adhesive referred to above for cryogenic tests. One longitudinal gage and one hoop gage were applied  $180^{\circ}$  from the weld and midway from the ends on the cylinders tested to determine weld strength. For tests to determine the yield and ultimate strengths of the parent tank material, pairs of hoop and longitudinal gages were applied  $\pm 90^{\circ}$  and  $180^{\circ}$  from the weld. An additional hoop gage was applied at one of the  $90^{\circ}$  stations; the signal from this gage was applied to one axis of an X-Y recorder in order to obtain a continuous pressure-versus-strain record. Pressure and the remaining strain gage signals were read out incrementally on a multichannel digital strain recorder.

The cylinders were pressurized to failure by applying helium pressure to water, liquid nitrogen or liquid hydrogen for tests at 70, -320, and -423 F, respectively. For the cryogenic tests, the cylinders were placed in a cryostat and both filled and surrounded with the appropriate cryogen.

In the linear stress-strain range pressurization of the unflawed cylinders was interrupted at each 100 psi pressure increment to allow recording of strain gage data. Pressure readings obtained from strain-gage-type pressure transducers were printed out before and after each pair of hoop and longitudinal strain gage readings. When a pressure of approximately 80 percent of the anticipated burst pressure was achieved, the strain recorder was made to print data at a rate of 4 channels per second and the cylinder was pressurized continuously to failure. This provided strain data in the nonlinear stress-strain range at each station at 5 to 10 psi increments in pressure.

Cracked cylinders were pressurized continuously to failure at a rate which ranged from 100 to 200 psi per minute. The pressure at which burst occurred was recorded. Accurate pressure readings were assured by calibrating the transducers with a high accuracy (within 3 psi) pressure gage before each test. Burst pressures ranged from 120 to 1850 psi.

Hoop stress  $\sigma$  was calculated from the pressure  $p$  using the relation  $\sigma = pr/t$  where  $r$  is the cylinder radius and  $t$  the wall thickness. Failure strengths were computed using the burst pressure. Yield strengths were obtained using the 0.2 percent offset method.

## Results and Discussion

### Uniaxial Properties

Smooth and notch properties for both alloys are plotted as a function of test temperature in Fig. 4. Specimens were tested with the loading direction both parallel (longitudinal specimen) and normal (transverse specimen) to the rolling direction. At least three specimens were tested for each condition. For both alloys only slight differences were found between the longitudinal and transverse yield and ultimate strengths indicating that, at least for these properties, the materials were essentially isotropic in the plane of the sheet. The Ti-5Al-2.5Sn ELI exhibited greater smooth uniaxial strength at all three test temperatures. The difference ranged from about 10 percent at room temperature to about 3 percent at -423 F.

Through-the-thickness, centrally cracked specimens were tested to determine the behavior of the two materials in the presence of a flaw. The Irwin method (11) was used to calculate fracture toughness. No effort was made to prevent buckling of the crack lips out of the plane of the sheet during testing. A limited number of tests using antibuckling face plates

indicated that buckling can reduce the calculated value of toughness by about 8 percent for the Ti-5Al-2.5Sn ELI alloy at -423 F. The error produced by the omission of antibuckling face plates at other temperatures for the Ti-5Al-2.5Sn ELI alloy was not determined, nor was the influence of buckling investigated for the Ti-4Al-0.2 O alloy at any temperature. However, since all notched uniaxial specimens reported here were tested without antibuckling face plates, the notch strength and fracture toughness values are considered comparable, though conservative.

A special point should be made regarding the thickness of the materials tested. As would be expected for sheet 0.020-inch thick, all specimen fractures were characterized by full shear fracture surfaces and accompanied by considerable plasticity. A rather complete statement of the effects of sheet thickness on the fracture toughness of Ti-5Al-2.5Sn alloy is reported in Ref. 12. It is important to recognize that the present results relate only to 0.020-inch thick material. While comparison of the two alloys investigated is justified on the basis of identical thicknesses, a comparison with the same or other alloys at thicknesses other than 0.020-inch is to be avoided.

As Fig. 4 shows, the Ti-4Al-0.2 O generally had a slightly higher notch-to-yield strength ratio (Fig. 4(b)) but a lower fracture toughness (Fig. 4(a)). The difference between test results using longitudinal and transverse specimens is again small except for Ti-5Al-2.5Sn ELI at -423 F where the transverse exceeded the longitudinal fracture toughness by about 10 percent. The cracked specimen was not sufficiently wide for obtaining valid toughness values at room temperature.

## Biaxial Properties

At -320 and -423 F the Ti-4Al-0.2 O cylinders generally failed immediately adjacent to the weld reinforcement. At -423 F failure occurred before the 0.2 percent offset strain was reached. Here the stress at burst is used as the yield strength. In Fig. 5 the biaxial yield and ultimate strengths are plotted as a function of test temperature for both alloys. To indicate the increase in yield strength predicted for an isotropic material, 1.15 times the average uniaxial yield strength is also included in this figure.

Both alloys developed biaxial yield strengths substantially greater than those predicted for isotropic materials. Strengthening ranged from 1.25 to 1.50 times the uniaxial yield strength. As would be expected, strengthening was greater for the more heavily textured Ti-4Al-0.2 O alloy at all temperatures investigated. Consequently, although Ti-4Al-0.2 O had lower uniaxial yield strengths than Ti-5Al-2.5Sn ELI at the three test temperatures, the biaxial yield strengths for both alloys at 70 and -320 F were nearly identical. At -423 F the Ti-4Al-0.2 O biaxial yield strength was about 9 percent greater than that of Ti-5Al-2.5Sn ELI.

Substantial increases in biaxial ultimate strength were also demonstrated by both alloys. In cases where failure occurred adjacent to the weld reinforcement, it is likely that the stress ratio at the failure location was less than  $1/2$ , and the values shown in Fig. 5 are probably lower than those which would be obtained in a true 1 to 2 stress field. At 70 and -320 F the percentage increase in failure strength, comparing biaxial to uniaxial results, is about the same as the percentage increase in yield strength for these two stress fields. At -423 F the ultimate strengths were only slightly

greater than the yield strengths.

In order to estimate the yield strengths of the two alloys in other stress fields, the experimental results were used to compute values of the strain ratio  $R$  in Eq. (1). These values are tabulated in Table 2. Then the computed values of  $R$  were used in Eq. (1) to calculate yield strengths in other biaxial stress fields. These projected yield strengths are shown in Fig. 6. At all three test temperatures the Ti-4Al-0.2 O yield strength is greater for stress ratios greater than 1/2. Another stress field of interest is the 1 to 1 ( $\alpha=1$ ) which occurs in a pressurized spherical shell. For this case the projected Ti-4Al-0.2 O yield strengths exceed those projected for Ti-5Al-2.5Sn ELI by 13, 9, and 16 percent at 70, -320, and -423 F, respectively. It is emphasized that these are projected strengths which have not been experimentally verified.

The results of the through-cracked cylinder tests are shown in Fig. 7. It has been demonstrated in Ref. (13) that the biaxial behavior of a material in the presence of a through-crack can be correlated with the uniaxial behavior by

$$\sigma_{hc} = \frac{K_{cn}}{\sqrt{\pi a_0 + \frac{1}{2} \frac{K_{cn}^2}{\sigma_{yb}^2} \left(1 + C \frac{a_0}{r}\right)}} \quad (3)$$

where  $\sigma_{hc}$  is the critical hoop fracture stress in the cylinder,  $K_{cn}$  is the nominal fracture toughness (based on initial crack length),  $a_0$  is the initial half crack length,  $\sigma_{yb}$  is the 1 to 2 biaxial yield strength,  $r$  is the radius of the cylinder, and  $C$  is a dimensionless bulge coefficient. The term  $1 + C \frac{a_0}{r}$  takes into account the increase in stress intensity at the crack tips in a pressurized cylinder due to bulging. The values of  $C$

used to draw the curves in Fig. 7 were obtained for each material and temperature by averaging the values of  $C$  computed using Eq. (3) for the individual data points. A weighted average described in Ref. (13) was used for both alloys. This average takes into account the greater sensitivity of cylinders with shorter crack lengths to an error in fracture toughness; consequently, it weighs the longer crack lengths more heavily. As  $a_0$  approaches zero, the critical hoop stress predicted by Eq. (3) exceeds the actual biaxial burst strength (i.e., at  $a_0 = 0$ ,  $\sigma_{hc} = \sqrt{2} \sigma_{yb}$ ). Therefore all curves in Fig. 7 are terminated at the biaxial ultimate strength in the region of small crack lengths.

For all the crack lengths tested, the Ti-4Al-0.2 O exhibited greater notch sensitivity than the Ti-5Al-2.5Sn ELI. Because the uniaxial fracture toughness properties of the two alloys were about the same, the relatively large difference in the biaxial results for longer cracks was not expected. A portion of the difference can be attributed to a higher residual stress condition in the Ti-4Al-0.2 O due to using a lower temperature and shorter time in the stress relief of these cylinders. By measuring the radius to which the cylinders opened when slit longitudinally, it was calculated that approximately 25 percent of the residual stress due to forming was still present in the Ti-4Al-0.2 O cylinders; this compares to less than 10 percent in the Ti-5Al-2.5Sn ELI cylinders. However, it is believed the amount of residual stress remaining in the Ti-4Al-0.2 O cylinders cannot account completely for the difference in the biaxial notch strengths. For small cracks (0.1 in. or less) it is likely that the difference between the notch strengths of the two alloys will be small.

Some of the ramifications of using biaxial yield strength in design

were brought to light during the biaxial test phase of this test program. It was stated in a preceding section that the Ti-4Al-0.2 O cylinders at -320 and -423 F frequently failed immediately adjacent to the weld reinforcement. The application of the reinforcement restrained the cylinders longitudinally in the vicinity of the weld. The stress ratio in the material immediately adjacent to the reinforcement was not 1/2 but something less than that, depending on the thickness of the reinforcement. As Fig. 6 shows, the Ti-4Al-0.2 O strength is quite sensitive to stress ratio and it is probable that its strength adjacent to the reinforcement was reduced sufficiently to cause failure there at cryogenic temperatures. The single cryogenically-tested Ti-4Al-0.2 O cylinder that failed away from the weld reinforcement had the reinforcement built up gradually in three increments. Each incremental layer was 0.004 inch thick and was 1/2-inch narrower than the preceding layer. This behavior indicates that thickness changes in textured metals should be made gradually and not abruptly.

#### Weld Strength

The uniaxial and 1 to 2 biaxial weld strengths of the Ti-4Al-0.2 O alloy are plotted in Fig. 8 as a function of test temperature. The biaxial weld strength of Ti-5Al-2.5Sn ELI at -320 F is included in this figure. In all cases the strength of the uniaxial Ti-4Al-0.2 O weld specimens was greater than that of the parent metal. Investigation of the uniaxial weld strength of Ti-5Al-2.5Sn ELI at 70 and -423 F has shown it to be very close to that of the parent metal (12).

Contrary to the uniaxial behavior, the biaxial weld strength was in all cases less than the biaxial ultimate strength. However, the Ti-4Al-0.2 O weld strengths at 70 and -320 F exceeded the biaxial yield strength. In all

cases the fracture occurred immediately adjacent to the weld bead. Biaxial weld data for Ti-5Al-2.5Sn ELI were obtained only at -320 F. While the parent biaxial yield strengths of the two alloys at this temperature were nearly identical, the biaxial weld strength of the Ti-4Al-0.2 O was about 17 percent greater than the Ti-5Al-2.5Sn ELI weld strength. The biaxial weld data obtained in this program are very limited. If subsequent tests produce the same results, Ti-4Al-0.2 O may have a considerable advantage over Ti-5Al-2.5Sn ELI in flaw-free, weld-critical, biaxially-stressed structures.

#### Correlation of Biaxial Strengthening and Plastic Poisson's Ratio

By combining Eqs. (1) and (2) and letting  $\sigma_x = \sigma_{yb}$  (biaxial yield strength), the ratio of 1 to 2 biaxial to uniaxial yield strengths can be written in terms of plastic Poisson's ratio as follows

$$\frac{\sigma_{yb}}{\sigma_{ys}} = \frac{2}{\sqrt{5 - 4\nu_p}} \quad (4)$$

This relation indicates that it should be possible to characterize texture strengthening in a sheet material by its plastic Poisson's ratio. In order to verify Eq. (4), values of  $\nu_p$  were obtained experimentally. These values are plotted in Fig. 9 versus average  $\sigma_{yb}/\sigma_{ys}$  obtained from pressure vessel tests. In Table 2 values are tabulated of average  $\sigma_{yb}/\sigma_{ys}$ , and  $\nu_p$  obtained experimentally, and R obtained from  $\sigma_{yb}/\sigma_{ys}$  using Eq. (1). Also included in this table are R and  $\sigma_{yb}/\sigma_{ys}$  predicted by average  $\nu_p$  using Eqs. (2) and (4), respectively.

In general using  $\nu_p$  to predict strengthening resulted in values close to those obtained experimentally. At 70 F, use of  $\nu_p$  resulted in predictions of strengthening greater than actually occurred while at -320 and -423 F the predictions were low. The greatest difference occurred with the



Ti-4Al-0.2 O alloy at -320 F where use of  $\nu_p$  resulted in a prediction 7 percent less than was obtained from pressure vessel tests. The relation between  $\nu_p$  and biaxial strengthening provides a relatively simple and inexpensive means of investigating the possibility of variation in texture strengthening within a sheet, from sheet to sheet of the same heat, and from heat to heat of the same alloy.

### Conclusions

Tests of Ti-4Al-0.2 O and Ti-5Al-2.5Sn ELI pressure vessels fabricated from 0.020 inch thick sheet showed significant increases in yield and ultimate strength in a 1 to 2 biaxial stress field over that obtained uniaxially. On the basis of biaxial yield and ultimate strength, Ti-4Al-0.2 O with a room temperature plastic Poisson's ratio of 0.845 ( $R = 5.45$ ) was generally superior to Ti-5Al-2.5Sn ELI (room temperature plastic Poisson's ratio of 0.732;  $R = 2.73$ ) at 70, -320, and -423 F especially when the experimental yield strength data was projected for stress ratios greater than one-half. For the limited data available, the Ti-4Al-0.2 O also exhibited superior weld strength. Ti-5Al-2.5Sn ELI developed greater biaxial notch strength for through cracks longer than about 0.10 inch. Consequently, the future improvement and use of the Ti-4Al-0.2 O alloy will probably be dependent upon the use of design and fabrication techniques which are able to take advantage of its superior yield and weld properties.

In designs based on the biaxial yield strength, care must be taken to insure that the stress field is as anticipated and not changed to a less-advantageous one in the presence of doublers, reinforcements, etc.

Use of the plastic Poisson's ratio obtained from a tension test to predict the amount of biaxial strengthening gave reasonably good results.

TABLE 2. . - AVERAGE UNIAXIAL AND BIAXIAL YIELD PROPERTIES

OF Ti-4Al-0.20 and Ti-5Al-2.5Sn ELI SHEET

Material	Temp., OF	Uniaxial yield strength, $\sigma_{ys}$ , KSI	1:2 Biaxial yield strength, $\sigma_{yb}$ , KSI	$\frac{\sigma_{yb}}{\sigma_{ys}}$	Strain ratio R (from Eq. 1)	Plastic Poisson's ratio, $\nu_p$	Strain ratio R based on $\nu_p$ (from Eq. 2)	$\frac{\sigma_{yb}}{\sigma_{ys}}$ based on $\nu_p$ (from Eq. 4)
Ti-4Al-0.20	70	94.4	144.6	1.53	4.70	0.845	5.45	1.57
	-320	157.1	222.5	1.42	3.06	.697	2.30	1.35
	-423	201.1	274.0	1.36	2.49	-----	-----	-----
Ti-5Al-2.5Sn ELI	70	104.9	143.8	1.37	2.55	.732	2.73	1.39
	-320	172.8	222.0	1.28	1.83	.617	1.61	1.26
	-423	203.5	252.4	1.24	1.53	.557	1.26	1.20

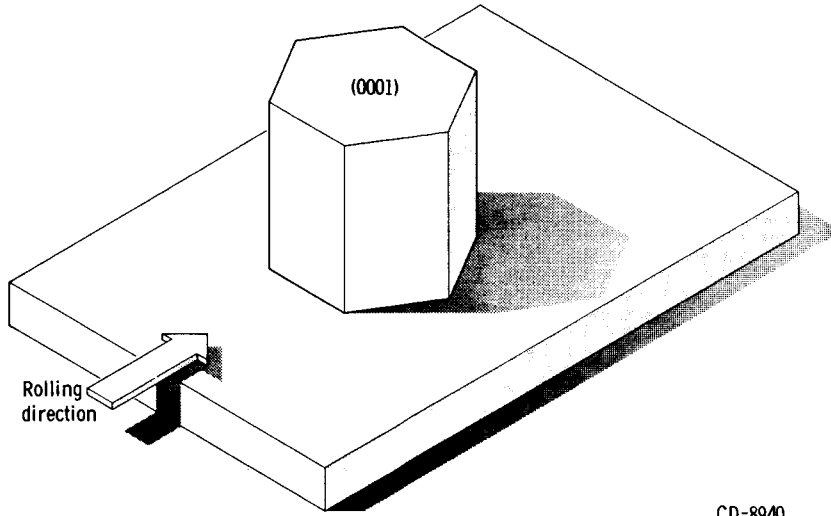
## References

1. W. A. Backofen, W. F. Hosford, Jr. and J. J. Burke, "Texture Hardening", Transactions, Am. Soc. Metals, Vol. 55, No. 1, Mar., 1962, pp. 264-267.
2. W. T. Roberts, "Preferred Orientation and Anisotropy in Titanium," Journal Less-Common Metals, Vol. 4, 1962, pp. 345-361.
3. F. R. Larson, "Anisotropy of Titanium Sheet in Uniaxial Tension," Transactions, Am. Soc. Metals, Vol. 57, No. 3, Sept. 1964, pp. 620-631.
4. A. J. Hatch, "Texture Strengthening of Titanium Alloys," Transactions, Am. Inst. Metallurgical Eng., Vol. 233, No. 1, Jan. 1965, pp. 44-50.
5. F. R. Larson, "Textures in Titanium Sheet and Its Effects on Plastic Flow Properties," Tech. Rep. 65-24, Army Materials Research Agency, 1965. DDC No. AD-626410.
6. J. L. Sliney, D. A. Corrigan and F. Schmid, "Preliminary Report on the Biaxial Tensile Behavior of Anisotropic Sheet Materials," Tech. Rep. 63-11, Army Materials Research Agency, 1963. DDC No. AD-421815.
7. H. W. Babel, D. A. Eitman and R. W. McIver, "The Biaxial Strengthening of Textured Titanium," Paper No. 3471, Douglas Aircraft Co., 1965.
8. R. Hill, "A Theory of the Yielding and Plastic Flow of Anisotropic Metals," Proceedings, Royal Soc., London, Vol. 193A, No. 1033, May 27, 1948, pp. 281-297.
9. T. L. Sullivan and T. W. Orange, "Continuity Gage Measurement of Crack Growth on Flat and Curved Surfaces at Cryogenic Temperatures," NASA TN D-3747, Nat. Aeronautics and Space Administration, 1966.
10. H. F. Calvert and R. H. Kemp, "Determination of Pressure Vessel Strengths at  $-423^{\circ}$  F as Influenced by Notches of Various Radii," Paper No. 520B, Soc. Automotive Eng., 1962.

11. ASTM Special Committee on Fracture Toughness Testing of High-Strength Metallic Materials, "Fracture Testing of High-Strength Sheet Materials," Bulletin, Am. Soc. Testing Mats., No. 243, Jan. 1960, pp. 29-40.
12. J. L. Shannon and W. F. Brown, "Effects of Several Production and Fabrication Variables on Sharp Notch Properties of 5Al-2.5Sn Titanium Alloy Sheet at Liquid Hydrogen Temperature," Proceedings, Am. Soc. Testing Mats., Vol. 63, 1963, pp. 809-823.
13. R. B. Anderson and T. L. Sullivan, "Fracture Mechanics of Through-Cracked Cylindrical Pressure Vessels," NASA TN D-3252, Nat. Aeronautics and Space Administration, 1966.

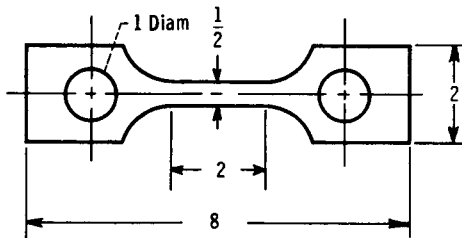
Footnote

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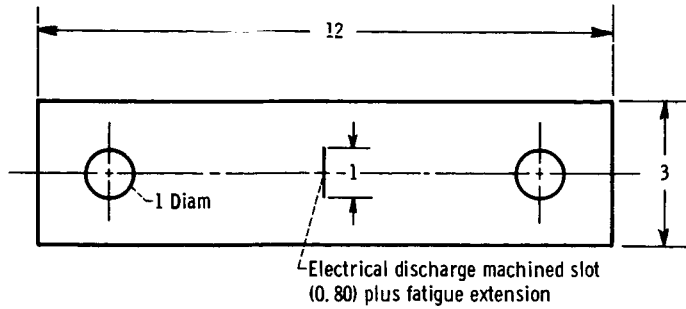


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Figure 1. - Ideal orientation of hexagonal close-packed crystal for maximum strengthening in a biaxial stress field.



(a) Smooth specimen.



(b) Center cracked specimen.

Figure 2. - Sheet tensile specimens (all dimensions in inches).

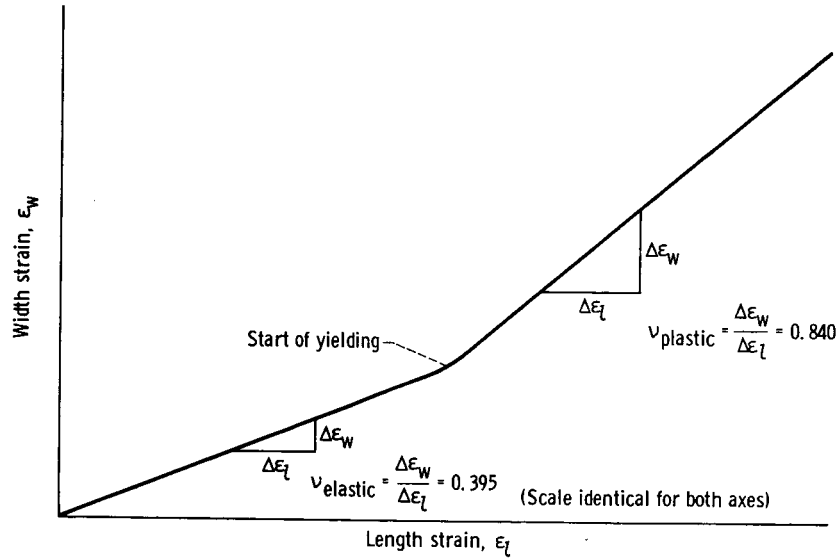
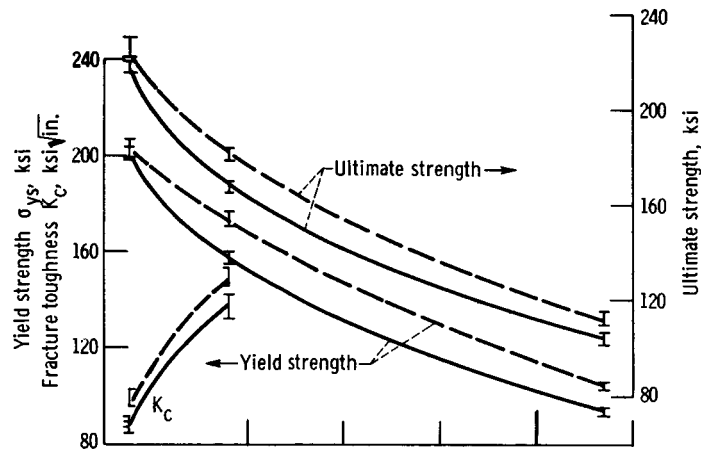
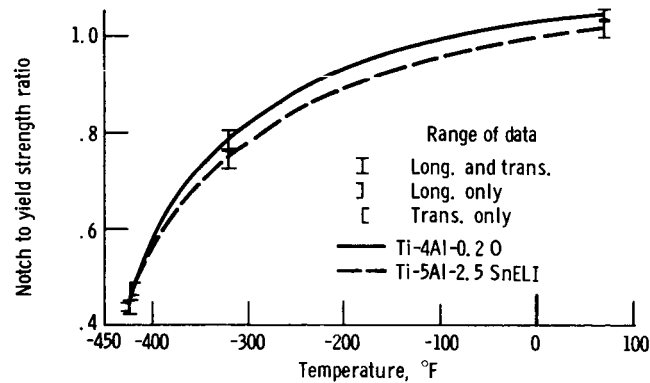


Figure 3. - Typical width strain against length strain record for Ti-4Al-0.2 O sheet at room temperature.



(a) Strength and toughness.



(b) Notch to yield strength ratio.

Figure 4. - Uniaxial properties of Ti-4Al-0.2 O and Ti-5Al-2.5 SnELI sheet as a function of test temperature.

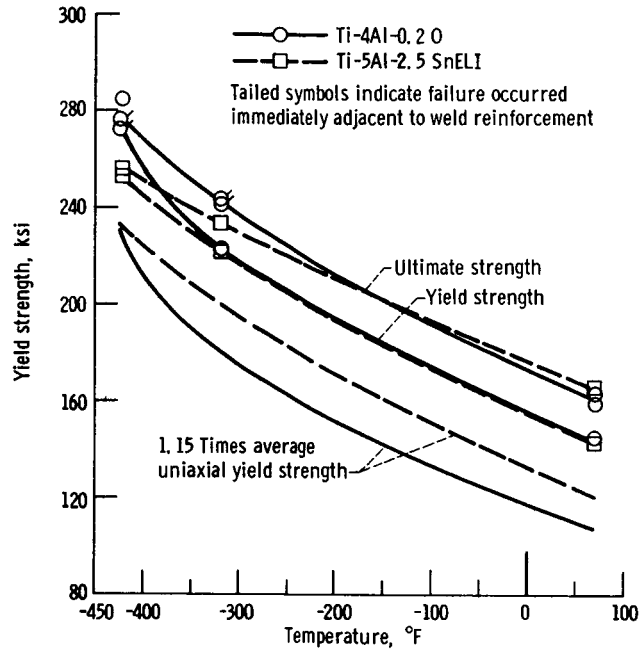


Figure 5. - 1:2 Biaxial yield and ultimate strength of Ti-4Al-0.2 O and Ti-5Al-2.5 SnELI sheet as a function of test temperature.

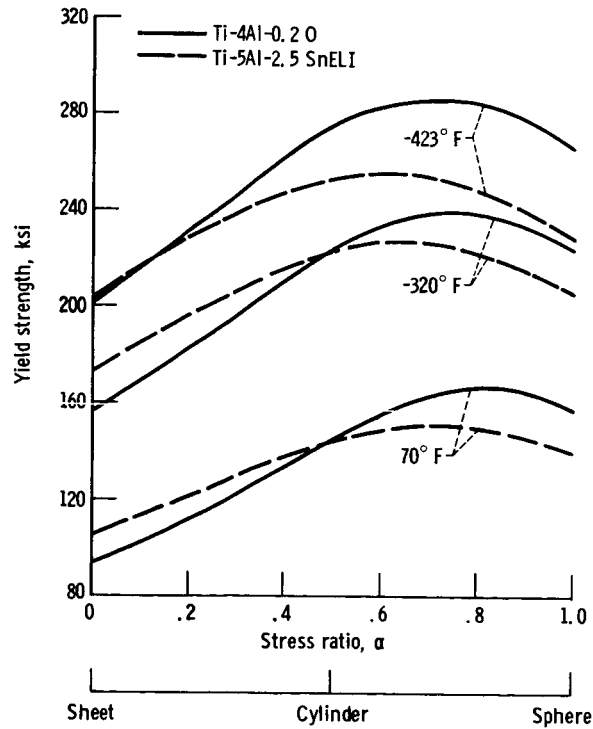


Figure 6. - Projected yield strengths for Ti-4Al-0.2 O and Ti-5Al-2.5 SnELI in a tension-tension biaxial stress field.



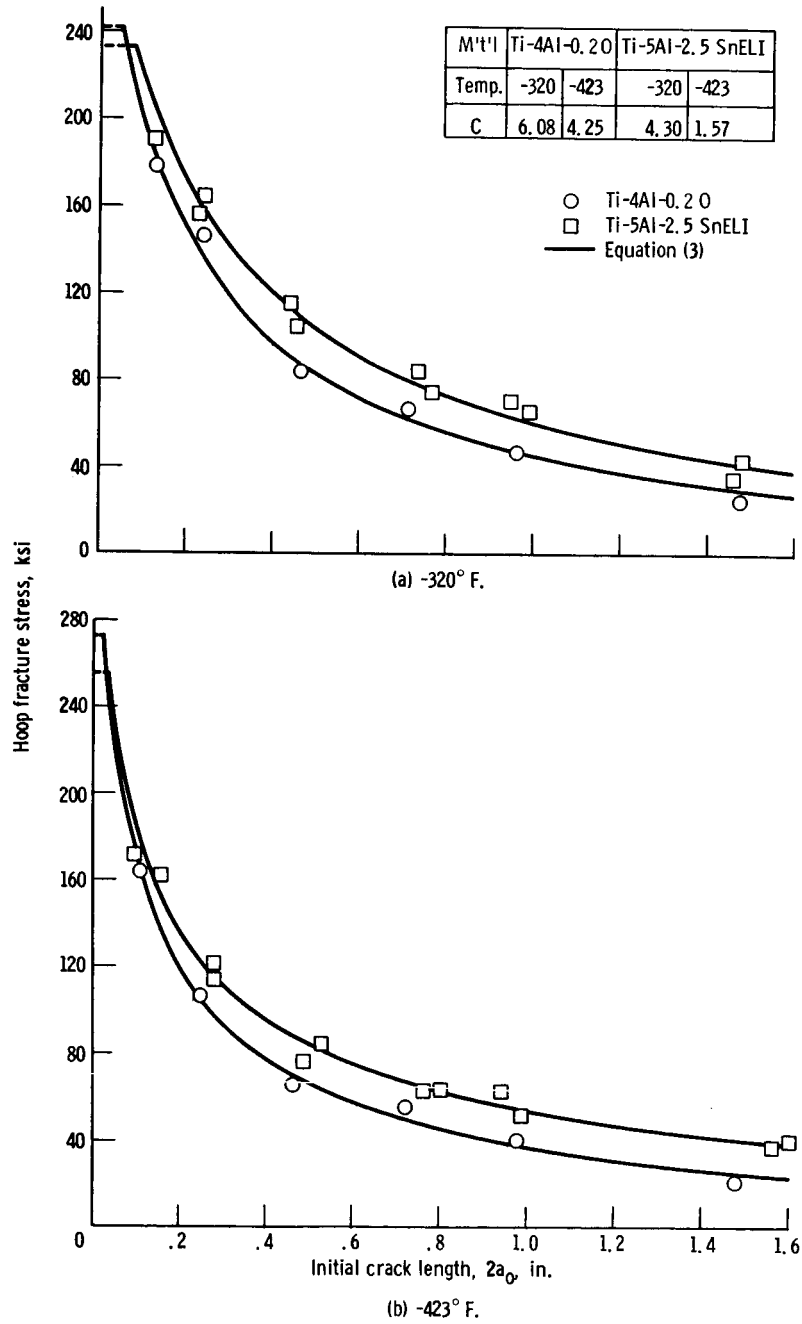


Figure 7. - Fracture strength of cracked titanium cylinders.

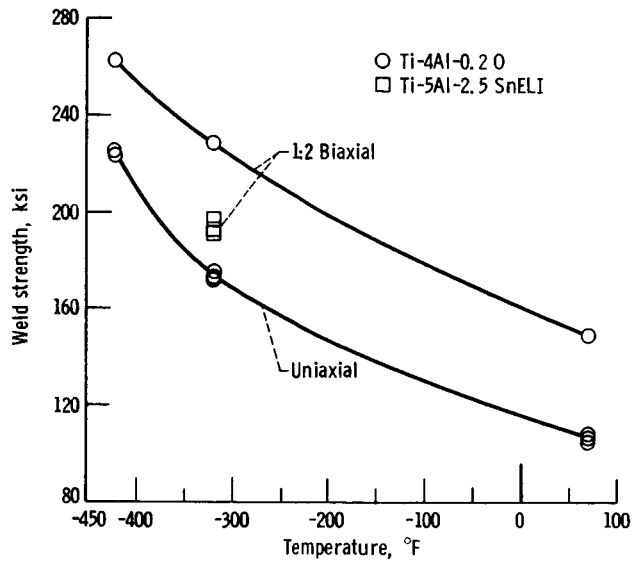


Figure 8. - Uniaxial and 1:2 biaxial weld strength of Ti-4Al-0.2 O and Ti-5Al-2.5 SnELI sheet as a function of test temperature.

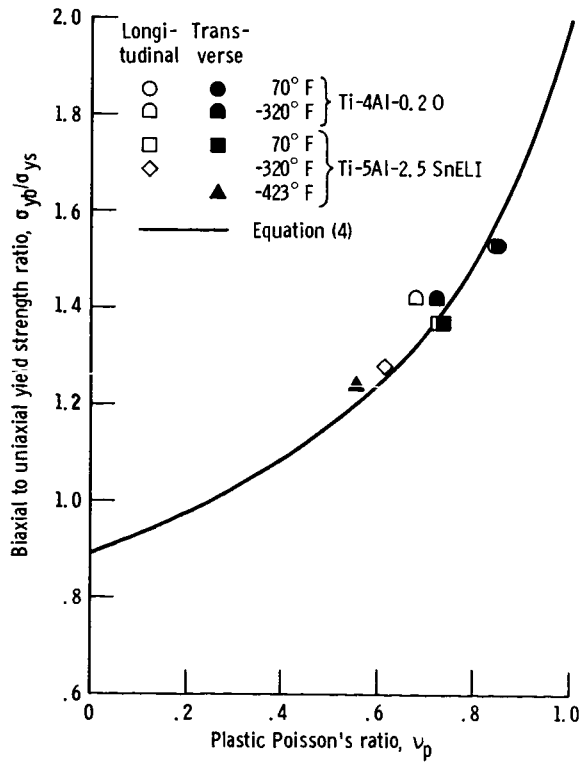


Figure 9. - Correlation of texture strengthening in a 1:2 stress field with plastic Poisson's ratio.