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THE EFFECTS OF TEXTURE AND STRAIN ON THE R-VALUE
OF HEAVY GAUGE TANTALUM PLATE

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ABSTRACT

PREVIOUS WORK BY OTHER RESEARCHES SUGGEST THAT THE R-VALUES MEASURED FROM THICK-GAUGE TANTALUM PLATE DO NOT CORRESPOND TO THE PREDICTED R-VALUES CALCULATED FROM ODF COEFFICIENTS. TO UNDERSTAND THIS BEHAVIOR, BULK TEXTURE ANALYSIS USING NEUTRON DIFFRACTION TECHNIQUES WAS CONDUCTED ON ANNEALED SAMPLES OF TA AND TA-2.5W PLATE: THE PURE TANTALUM EXHIBITED A PRIMARY {111} TYPE TEXTURE WHEREAS THE ALLOY CONTAINED A CUBE TEXTURE. FOR THE PURE TANTALUM, THE R-VALUES CALCULATED FROM THE TEXTURE OF AS-ANNEALED AND THE DEFORMED SPECIMENS WERE SIMILAR AND CORRELATED WELL WITH MEASURED DATA. THE R-VALUE OF THE TA-2.5W EXHIBITED A GREATER DEGREE OF STRAIN-SENSITIVITY, SUCH THAT THE CALCULATED R-VALUES BASED ON THE INITIAL TEXTURE DID NOT REPRESENT THOSE CALCULATED OR MEASURED AFTER TENSILE DEFORMATION. STRAIN SENSITIVITY OF R-VALUES IN TA AND TA-2.5W PLATES IS RELATED TO THE GENERATION OF A $\langle \bar{1}10 \rangle$ FIBER TEXTURE DURING DEFORMATION.

INTRODUCTION

Tantalum is a high-density bcc refractory metal which is used in a variety of specialized applications[1] which range from high-reliability capacitors for electronic components to corrosion resistant conduits and linings for the chemical processing industry. Tantalum's combination of low flow stress, high ductility, and favorable texture lends itself for use in deep-drawing: thin-gauge tantalum strip (>0.40 mm) is deep drawn to form wet capacitor cans; thin-gauge plate (0.40 - 4.0 mm) is conventionally drawn into laboratory crucibles; and moderate-gauge plate (4.0 mm- 6.6 mm) is explosively formed into armor-piercing long-rod penetrators.

There has been recent interest to use heavy-gauge tantalum and Ta-W alloy plate (<4.0 mm) for deep-drawing. However, researchers found that the r -value data calculated from X-ray diffraction pole figures did not reflect those measured instantaneously from tensile samples.

BACKGROUND

The formability of a metal sheet, specifically its ability to be deep-drawn into a cup or conical shape, is critically dependent on the isotropy of the material. Lankford et al [2] are recognized as the first to correlate the drawability of steel to a strain ratio, termed an r -value:

$$r = \frac{\epsilon_N}{\epsilon_T} = \frac{\ln(1+\epsilon_N)}{\ln(1+\epsilon_T)} \quad (1)$$

Typically, the r -value (also known as the Lankford parameter) will vary within the plane of the sheet with respect to the rolling direction. For this reason, an "average" r -value, termed r_m , is often cited as a measure of the normal anisotropy in a plate:

$$r_m = \frac{r_0 + 2r_{45} + r_{90}}{4} \quad (2)$$

A material exhibiting a high r_m will preferentially deform in the plane of the sheet by resisting through-thickness thinning. Hence, increased r_m -values have been related to improved drawability[2] as well as to greater dent resistance[3] and reduced edge splitting[4] in steel sheets.

The effect of a variation in r -value with directions parallel to the plane of the sheet results in the formation of ears on the flange during deep-drawing. The tendency of earing is generally represented by Δr :

$$\Delta r = \frac{r_0 - 2r_{45} + r_{90}}{2} \quad (3)$$

The development of mechanical anisotropy and r -values in sheet steels is related to the crystallographic texture of the annealed

product. Numerous researchers have shown that an increased r-value is obtained in steels which have a large volume fraction of (111) planes oriented in the plane of the sheet, while a significant (100) texture component normal to the surface is considered detrimental to deep drawability[5,6,7,8,9,10]. Held[11] has demonstrated that the r-value can be correlated to a ratio of the intensities of the (111) and (100) texture components measured by X-ray diffraction. Hence, much of the research in alloy development on processing of sheet steel focuses on increasing the concentration of the (111) component and/or decreasing the level of (100).

With the advent of the Orientation Distribution Function (ODF), a method of calculating theoretical r-values directly from pole figure data was derived using a mean Taylor factor and ODF coefficients[12]:

$$r(\beta) = \overline{r} + (r^1 \cdot C_4^{11}) + (r^2 \cdot C_4^{12} \sin 2\beta) + (r^3 \cdot C_4^{13} \sin 4\beta) \quad (4)$$

where $r(\beta)$ = r-value along the β direction in the plate
 r^i = constants which can be determined from Taylor Theory
 $C_4^{\mu\nu}$ = ODF Coefficients

For bcc materials, such as low-carbon steel, which slip on (hkl)<111> systems (pencil glide), Equation 4 has been successful in approximating the variation in r-values measured along different β directions[13,14], but has been found to overpredict r-values when compared to measured data[15]. Therefore, the objective of this effort was to gain insight of the mechanism responsible for the r-value variation resulting from uniaxial strain.

EXPERIMENTAL PROCEDURE

The tantalum used for this effort was produced from a triple electron beam melted (3EB) electrode which was vacuum arc remelted (VAR) to yield a 305 mm (12") diameter ingot. The ingot was press forged and machined into slabs. The mulds were annealed and cold rolled perpendicular to the ingot axis to a total reduction of 92%. The Ta-2.5 material was fabricated from a 255 mm (10") diameter 3EB melted ingot which was side forged, cut into slabs, machined, then annealed. The Ta-2.5W slab was transverse rolled to a cold reduction of 87%. The rolling direction for the Ta-W alloy was defined as the rolling direction of the last pass through the mill. The Ta and Ta-W alloy were annealed at temperatures which yielded a common grain size of 50-55 μm , as measured by the linear intercept method. Chemical analyses of the pure and alloy plate are provided in Table I.

Texture analysis was conducted on samples removed from both the center and edge of each plate and mounted on a four-circle neutron diffractometer at the National Institute for Standards and Technology (NIST). Using 0.208 nm neutron radiation, the (200), (110), and (211) pole figures were measured over the entire orientation hemisphere at 5° intervals. The raw diffraction data was corrected for background radiation and absorption, then normalized to provide

Table I: Chemistry of Ta and Ta-2.5W Plate (ppm by weight except where noted).

	O	C	N	H	W	Nb	Mo	Fe	Cu
Ta	<10	<10	<10	<5	35	<25	<5	<5	<5
Ta-2.5W	<10	<10	<10	<5	2.9%	1160	<5	10	<5

pole figures in units of random distribution densities. ODF calculations were performed using the *popLA* program developed by Los Alamos National Laboratory[16]. The theoretical r -values were calculated by harmonic analysis.

To evaluate the effect of strain on the texture of each material, a longitudinal tensile specimen (design 1) was uniaxially strained to $\epsilon=0.30$ then analyzed using neutron diffraction. R -values were recalculated using the texture data measured after straining.

Tensile specimens were machined with their axes oriented in the longitudinal (0°), transverse (90°), and 45° directions with respect to the rolling directions. Three tensile bars designs having a 25.4mm (1.0") gauge length but differed in cross-section geometry were employed for this study: design 1 had a 7.62 ± 0.13 mm square cross-section; design 2 had a 6.35 ± 0.13 mm diameter cross section; and design 3 had 5.59 ± 0.13 mm square cross-section. Samples were pulled on a screw-driven Instron tensile machine at a crosshead speed of 1.27mm/min. (0.05"/min.). Widths and thickness strains were measured at the center of the gauge section using a pin micrometer (strain gauges could not be used due to the high ductility of the materials). Measurements were taken at 1 minute increments until ultimate strain was reached. Instability occurred at strains slightly above 0.34 in several of the Ta-2.5W tensile specimens. Therefore, the $r_m^{0.3}$ -values reported herein represent the average of the measurements at 0.26, 0.30, and 0.34 true strain.

RESULTS

The pure tantalum contained strong $\{111\}\langle\bar{1}12\rangle$, $\{334\}\langle\bar{8}43\rangle$, and $\{111\}\langle uvw \rangle$ components and moderate $\{001\}\langle uvw \rangle$ and $\{114\}\langle\bar{1}10\rangle$ components. The tensile specimen deformed to a true strain of 0.30 contained equally strong $\{111\}\langle\bar{1}10\rangle$, $\{223\}\langle\bar{1}10\rangle$, $\{111\}\langle uvw \rangle$, $\{001\}\langle\bar{1}10\rangle$, and $\{114\}\langle\bar{1}10\rangle$ components. The as-annealed Ta-2.5W consisted of a primary $\{001\}\langle\bar{1}00\rangle$ cube texture and a weak $\{116\}\langle\bar{5}01\rangle$ component, whereas the deformed sample contained a primary $\{001\}\langle\bar{1}10\rangle$ texture and the weak $\{116\}\langle\bar{1}10\rangle$ component. Little difference was evident in the texture measured at the center and edge locations of the pure Ta or Ta-2.5W plates.

The r -values predicted from the texture data obtained from each of the starting plates and from longitudinal tensile specimens deformed in tension to a true strain of 0.30 is presented in Table II. Based on texture of as-annealed and deformed tantalum, little variation is predicted in r_0 with strain. However, the r_m and Δr values are predicted to vary with strain. Caution must be taken with

regard to the predicted r_m and Δr values since the r_{45} and r_{90} values used in the calculations are based on the texture of one sample deformed in the rolling direction. A better assessment on the effects of strain on the calculated r_m and Δ values should be made using texture data from samples deformed in transverse and 45° directions.

For the Ta-2.5W alloy, due to the differences between the undeformed and deformed materials, a decrease in r_0 and r_{90} , and an increase in r_{45} is expected during deformation. The variation in r_0 with strain for Ta and Ta-2.5W is presented in Figures 1 and 2, respectively. The r_0 values for each material calculated from the texture of the as-annealed ($\epsilon=0$) and the deformed samples ($\epsilon=0.3$) is

Table II: R-Values of Ta and Ta-2.5W Plate. Calculated Values Determined By Harmonics Analysis of Diffraction Data Assuming Pencil Glide; Measured Values Determined by Tensile Testing.

CALCULATED					
n^0 SAMPLE	r_0	r_{45}	r_{90}	r_m	Δr
Ta (Center)	1.1	0.7	1.7	1.0	0.6
Ta (Edge)	1.2	0.8	1.8	1.1	0.7
Ta ($\epsilon=0.30$)	1.2	1.0	0.5	0.9	-0.1
Ta-2.5W (Center)	0.9	0.4	1.3	0.8	0.7
Ta-2.5W (Edge)	1.2	0.4	1.3	0.8	0.8
Ta-2.5W ($\epsilon=0.30$)	0.8	0.5	0.8	0.6	0.3
MEASURED					
TENSILE SAMPLE	$r_0^{.30}$	$r_{45}^{.30}$	$r_{90}^{.30}$	$r_m^{.30}$	$\Delta r^{.30}$
Ta (Design 1)	1.2	0.7	1.3	1.0	0.6
Ta (Design 2)	1.4	0.6	1.3	1.0	0.8
Ta (Design 3)	1.2	1.1	1.3	1.2	0.2
Ta-2.5W (Design 1)	0.8	0.5	1.0	0.7	0.4
Ta-2.5W (Design 2)	0.6	0.5	0.9	0.6	0.3
Ta-2.5W (Design 3)	0.7	0.6	1.1	0.7	0.4

Figure 1: Variation in r_0 with Strain for Ta Plate. **Figure 2:** Variation in r_0 with Strain for Ta-2.5W Plate.

NOTE: Heavy Solid and Dashed Lines Represent r_0 -Values Predicted from Texture Analysis (Assuming Pencil Glide) of As-Annealed and Strained Specimens, Respectively.

represented as horizontal lines in Figures 1 and 2. It can be generalized that the measured r_0 decreases with strain; the trend is most apparent in the (111) textured Ta. The r_0 -values predicted from the texture of the as-annealed Ta-2.5W alloy is an overestimate of the r_0 -value measured during plastic deformation. However, the r_0 calculated from the texture measured from a longitudinal tensile specimen deformed to a true strain of 0.30 closely resembles those measured at a similar strain level.

DISCUSSION

It has been observed that the r -value of many materials changes with increasing strain. Comparisons of the strain dependance of r -values in aluminum-killed and titanium bearing steels lead researchers to conclude that a variation in r -value with strain (beyond the Luders range) is associated with the interstitial content of the metal[17]. It is unlikely that interstitials are a major factor in the strain sensitivity of r -values in Ta and Ta-2.5W because of the low concentrations measured in the materials.

Hu[18] demonstrated that the change in r -value with strain was dependent on the initial r -value of the steel being tested: r -values decreased with strain for strongly (111) textured steel and increased with strain for steels having an initial r -value less than unity. This behavior was rationalized by Hu based on the difference in through-thickness and in-plane work-hardening exponents of the deep-drawing steel. (111) textured material exhibited a higher flow stress and lower work-hardening exponent (which Hu correlated to a greater work-hardening rate) in the through-thickness direction than in the

plane of the sheet; the opposite was true for the (001) textured, low r -value sample[19]. However, the work-hardening rate, determined by differentiating the Ludwig equation, is dependent on both n and K , and n alone is insufficient to describe the work-hardening rate (θ).

Polycrystalline (111) tantalum and Ta-2.5W have been shown to exhibit a greater flow stress the normal direction than in the in-plane directions; the work hardening rates measured in the normal direction for Ta and Ta-2.5W were similar to those found along the longitudinal direction of each alloy[20]. It unclear why the (100)<001> textured Ta-W alloys exhibit the same trends in orientation-dependent mechanical behavior as gamma-fiber textured tantalum. However, these results indicate that differential work-hardening behavior alone does not predict the strain-sensitivity behavior of Ta and Ta-2.5W.

Truszkowski[21] speculated that the change in r -value with strain in fcc aluminum and nickel is due to the formation of a fiber texture during tensile deformation, although no texture information was provided to support this claim. From the comparison of the texture results on as-annealed and deformed Ta and Ta-2.5W, it is shown that tensile strain acts to orient all slip directions to $\langle \bar{1}10 \rangle$. Rolling direction inverse pole figures of as-annealed and axially strained tantalum and Ta-2.5, provided in Figures 3 and 4, reveal the reorientation of the tensile axes toward $\langle \bar{1}10 \rangle$.

For the pure material, the rotations of the primary components $\{111\}\langle 112 \rangle$ and $\{334\}\langle \bar{8}43 \rangle$ to $\{111\}\langle \bar{1}10 \rangle$ and $\{223\}\langle \bar{1}10 \rangle$ likely do not have an overbearing influence on the strain sensitivity of the r -value. However, a $\{100\}\langle \bar{1}10 \rangle$ orientation has been predicted to have relatively low r_0 value[22]. The formation of the $\{100\}\langle \bar{1}10 \rangle$ from a $\{100\}\langle uvw \rangle$ fiber may account for the measured decrease in r_0 in Ta with strain. Since there is a relatively low concentration of $\{100\}\langle uvw \rangle$ component in the as-annealed Ta, it is expected that the fiber component would be quickly consumed, and the r -value would then be a constant value with respect to subsequent strain. The finding herein that the calculated r -values of the as-annealed and deformed Ta

Figure 3a: Rolling Direction Inverse Pole Figure of As-Annealed Ta.

Figure 3b: Rolling (Tension) Direction Inverse Pole Figure of Ta Deformed $\epsilon=0.30$ in Tension.

Figure 4a: Rolling Direction Inverse Pole Figure of As-Annealed Ta-2.5W.

Figure 4b: Rolling (Tension) Direction Inverse Pole Figure of Ta-2.5W Deformed $\epsilon=0.30$ in Tension.

material are similar, while the measured r_0 -value (for full thickness tensile specimen) is nearly constant beyond a true strain of 0.20. support this claim.

In the Ta-2.5W plate, the final $\{100\}\langle\bar{1}10\rangle$ texture is expected to have lower r -value than expected from the initial $\{100\}\langle\bar{1}00\rangle$ texture[22]. Therefore, the reduction in r_0 with strain for Ta-2.5W is due to the rotation of the slip directions towards $\langle\bar{1}10\rangle$. Since the primary texture of the Ta-2.5W alloy is $\{100\}\langle\bar{1}10\rangle$, a significant decrease in r -value is expected during deformation. This behavior was predicted from the textures of the as-annealed and strained alloy.

CONCLUSIONS

The r_0 -value predicted using texture information from the as-annealed Ta is similar to both that predicted from the texture of an axially deformed tensile specimen and that measured (beyond a true strain of 0.20). The lack of strain-sensitivity of the Ta has been associated with similarities in r -values behavior based on the initial texture components and the $\langle\bar{1}10\rangle$ fiber components identified after deformation.

The strain-sensitivity of the Ta-2.5W alloy is due the rotation of the as-annealed $\{001\}\langle 100\rangle$ cube texture towards $\{001\}\langle\bar{1}10\rangle$. The r_0 -value of the $\{001\}\langle\bar{1}10\rangle$ orientation is lower than that for the $\{001\}\langle 100\rangle$, and r -value decreases with strain while rotation occurs.

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