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Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115 and Livermore, California 94550 for the United States Atomic Energy Commission under Contract AT (29-1) 789

May 1975

Sandia Laboratories

SF 2900 Q(7-73)

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ABSTRACT

The mechanical properties of 1100 aluminum prepared by plasma spraying and hot pressing 1100 aluminum powder have been determined. The structure and composition of the material was representative of conditions likely to be found in popular aluminum-matrix composites. The yield and ultimate strengths of the material fall between those of wrought 1100 aluminum and sintered aluminum powder (SAP) of similar oxide content. Measurement of Poisson strains in directions parallel and perpendicular to the direction of hot pressing showed that the material was plastically, but not elastically, anisotropic. The strain-rate sensitivity of the plasma sprayed aluminum was similar to that of commercial 1100 aluminum.

These results provide additional insights for fabrication of composites from this matrix system, and for interpreting or predicting the mechanical properties of those composites.

*This work was supported by the U.S. Energy Research & Development Administration.

1. INTRODUCTION

Metal-matrix composites are fabricated by a number of techniques [1], the choice of which depends upon the constituent materials, composite geometry and desired mechanical and physical properties. One method that is frequently utilized [2,3] involves matrix deposition by plasma spraying, either directly in conjunction with a filament winding operation or through manufacture of monolayer tapes which are then diffusion bonded in the desired orientations. These processes permit a large number of material combinations, fiber volume fractions, and fiber orientations to be achieved. Their disadvantage is the porosity which is present in the as-sprayed matrix. To achieve optimum composite properties it is necessary to densify the matrix; densification is generally accomplished by a hot pressing operation which produces diffusion bonding. The resulting matrix material is similar to that produced by powder metallurgy techniques.

Aluminum and aluminum alloys are frequently used for the matrix in lightweight, high performance composites; boron-aluminum composites prepared by plasma spraying are commercially available.* Micromechanical analysis and prediction of composite behavior requires knowledge of the properties of both the fibers and matrix. Little, if any, data is available on mechanical properties of plasma-sprayed aluminum. The 1100 aluminum alloy was selected for this investigation to supplement data previously obtained on composites having this matrix [3-6] and to avoid the complications caused by alloy-strengthened matrices. It has been demonstrated [7] that plasma sprayed aluminum powder which is then hot pressed results in an oxide

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dispersion strengthened material. Proper selection of hot pressing conditions yields a material having strength similar to that of sintered aluminum powder (SAP) of the same oxide content [7]. The pressing conditions which produce high-strength, plasma-sprayed aluminum are not optimum for composite fabrication, so the matrix in these composites is anticipated to have properties whose values fall between those of O Temper 1100 aluminum and SAP.

The present investigation was undertaken to determine the mechanical properties of plasma-sprayed aluminum under processing conditions representative of the matrix in a composite. Hot pressing parameters have been varied to determine the sensitivity of matrix mechanical properties to relatively small variations in fabrication conditions, such as might be expected to occur in fabrication of parts of large size or complex geometry. In addition, since plasma spraying produces an oriented microstructure which is retained when the spraying and pressing directions coincide, the mechanical anisotropy of the material has been examined.

2. EXPERIMENTAL

One inch thick plates of material were prepared by plasma-spraying Metco 1100 aluminum powder onto a rotating dodecahedral mandrel. The spraying parameters, summarized in Table I, are those used in this laboratory for fabrication of reinforced-aluminum composites. Study of the effect of all plasma spraying variables *per se* is beyond the scope of this investigation. Nominal chemical analysis of the starting powder is given in Table II. All specimens used in this study were machined from this one build-up of sprayed aluminum. The as-sprayed plates were placed in stainless steel bags under a protective argon atmosphere and crimped shut to

provide a mechanical seal. Hot pressing was carried out without further atmospheric protection, under conditions summarized in Table III. Stops were placed between the hot platens to limit the deformation to 50 or 63 percent reduction in thickness. These values approximate the range of reductions obtained during hot pressing of boron-aluminum composites.

Round tensile test specimens, 7.6 cm long with a 5.1 cm gage length, were machined from the densified plates. Strain gages were used at all test temperatures. For the room temperature Poisson's ratio measurements, biaxial strain gages were mounted at 90 degree orientations around the gage section. The axis of the specimens lay in the plane of pressing and parallel to the rotational axis of the mandrel used for plasma spraying. The strain gages were oriented such that in addition to axial strains, transverse strains parallel to and perpendicular to the direction of hot pressing were recorded separately. Room temperature testing was performed on an Instron machine. Elevated temperature tests were performed on a Baldwin test machine equipped with a resistance heated furnace. Strain rates were varied between 0.005 and 0.050 $min.^{-1}$.

3. RESULTS

3.1. Stress-Strain Behavior

The ultimate tensile and 0.2 percent offset yield strengths of plasma-sprayed aluminum were higher than the corresponding values for 1100-0 aluminum, and below those of SAP, as summarized in Table IV. The relative strengths of the three materials are in the same ratio for all temperatures up to 427°C as seen in Figure 1. The ductility of the plasma-sprayed aluminum varied dramatically. Specimens from two of the hot-pressed plates consistently exhibited 20 to 30 percent elongation-to-fracture, comparable

in magnitude to the elongation reported for SAP [8]. The fracture surfaces of the ductile specimens, Figure 2a, exhibited the dimpled microstructure characteristic of ductile rupture. Specimens from the other plates, however, failed at strains between 4 and 8 percent. In this case the fracture surface, Figure 2b, was different, exhibiting a layered structure defined by fracture which appeared to propagate along the boundaries of the elongated plasma sprayed particles. The hot pressing conditions for each plate are summarized in Table III along with the room temperature mechanical properties. The changes in ductility could not be correlated with oxide content or hot pressing temperature.

There was relatively little difference in the initial portions of the stress-strain curves for the different hot pressing conditions utilized in this study. The small-strain portions of the curves at room temperature for specimens pressed at different temperatures are shown in Figure 3. The resulting changes in yield and ultimate tensile strengths were not large; they were only slightly greater than the range of scatter observed in tests on specimens having the same fabrication history. The variation in strength with hot pressing temperature is shown in Figures 4a and 4b. Although only one specimen was tested at a given condition the data, particularly for yield strength, indicates a decrease in strength with increasing hot pressing temperature. Increasing the amount of deformation during pressing from 50 to 63 percent produced a slight increase in subsequent yield strength, as indicated in Table III. For comparison, increased deformation had less effect on yield strength than lowering the temperature of subsequent deformation by 10°C.

3.2. Strain-Rate Sensitivity

Stress strain curves obtained at strain rates between 0.005 and 0.050 min^{-1} showed some evidence of a strain-rate sensitivity, but the effect was initially somewhat obscured by specimen-to-specimen variation of the flow stress. Strain-rate cycling tests on individual specimens eliminated the variability problem, and a small strain rate-sensitivity was revealed.

Activiation volumes were calculated from the differential rate measurements using the well-known relationship

$$V^* = -Kt \left(\frac{\partial \ln \dot{\epsilon}}{\partial \tau}\right)_T \quad . \tag{1}$$

These results are shown in Figure 5 for test temperatures between 25° and 260°C as a function of hot-pressing temperatures. For a given hot-pressing temperature, the activation volume decreased with test temperature. At a given test temperature, the activation volume increased slightly with increasing hot pressing temperature. The activation volume was independent of strain for all test conditions.

3.3. Poisson's Ratio

Poisson's ratio for isotropic materials is an elastic constant related to the material elastic moduli. With the onset of plastic deformation Poisson's ratio ceases to remain a material elastic constant but may still be regarded as a ratio of transverse and longitudinal strains. In this regard, then, the elastic and plastic Poisson's ratio were determined as a function of strain at room temperature for specimens hot pressed at each of the three temperatures. The results are summarized in Figure 6. In the elastic region, Poisson's ratio for all specimens was in good agreement with the value of 0.33 reported for wrought aluminum [9,10]. In the plastic

domain, where the anisotropic nature of the material was most evident, Poisson's ratio increased asymptotically with strain to a limiting value, as normally observed in metals. The magnitude of the asymptotic plastic Poisson's ratio depended upon the orientation of the gages measuring the transverse strain. When the transverse strain was measured parallel to the direction of pressing the asymptotic Poisson's ratio was 0.52, higher than for wrought aluminum. In the direction perpendicular to the direction of pressing, however, the asymptotic Poisson's ratio was 0.41 which is lower than that for wrought aluminum.

4. DISCUSSION

4.1. Stress-Strain Behavior

It is well documented [8] that the fineness of the dispersed phase is of paramount importance in the strengthening process for aluminum alloys. The oxide content of the material used in this study was nearly the same as that studied by Schuster and Moss [7]; however, the less severe fabrication conditions (less mechanical working and higher temperatures) for the plasma sprayed aluminum of this investigation could lead to differences in the dispersion of the oxide phase and in the dislocation density. A distribution of larger oxide particles and lower dislocation density would account for the reduced strength of the material studied in this investigation. This explanation is consistent with the trend of increasing strength with lower hot pressing temperature and increased reduction in thickness.

The wide range of ductilities between specimens from the different hot pressed plates cannot be explained by differences due to the plasma spray process since all material was fabricated in one operation. There

is a small variation in oxide content, as shown in Table III, but the variation does not correlate with the changes in ductility. The ductility of SAP alloys reported in the literature varies with oxide content from 23% at 1.6 w/o oxide to 6-17% at 6-8 w/o oxide. In view of the published results, the small variation in oxide content between the different plates in this investigation would not account for the magnitude of the ductility changes observed. In addition, these published reports indicate that the decrease in ductility of SAP with an increase in oxide content is accompanied by an increase in yield strength. This trend was not observed in the plasma sprayed material. The only difference in processing conditions that correlated with the observed changes in ductility was the elapsed time between bagging the specimens under argon and carrying out the hot pressing operation (Table III). Since only a mechanical seal was used to contain the protective gas it is expected that the longer time would result in more air leaking into the container. With a contaminated argon atmosphere it is possible that additional oxide or other impurities in amounts not discernable within the range of values obtained in the chemical analysis might form on the surface of interconnected pores in the as-sprayed material. This would result in weak interfaces between the plasma sprayed particles, lowering the ductility and producing the fracture morphology seen in Figure 2b. It is not necessary that the shape of the stress-strain curve be changed by such a mechanism. In the case of low alloy steel forgings, local composition inhomogeneities allegedly [11] influence only the fracture mode and remain relatively unimportant in limiting the strength properties.

From a practical standpoint the low ductilities (4-8 percent) are not of major concern, especially in the case of unidirectional reinforced composites where failure of the typical reinforcement (boron or Borsic fibers)

occurs at less than one percent strain. In the case of ductile fibers such as beryllium, where elongations as high as 10% have been reported [5], the fabrication procedure must be carefully controlled to avoid having the composite strength limited by matrix failure.

4.2. Strain-Rate Sensitivity

There is little data in the literature suitable for direct comparison with the strain-rate sensitivity data of this study. Guyot [12] reported activation volumes for SAP alloys deformed at room temperature in the range 2 to 5 x 10^{-21} cm^3. These are considerably smaller than the room temperature activation volume of 36 x 10^{-21} cm^3 obtained in this investigation for plasma sprayed aluminum under comparable strain and strain-rate conditions. In both cases, the data were obtained using differential strain-rate tests. The strain-rate sensitivity of aluminum alloys has been investigated by Holt, et al. [13]. They reported activation volumes between 2 and 4 x 10^{-21} cm^3 for 1100-0 aluminum at strain rates above 0.3 sec^{-1}. At lower strain rates, comparable to those used in the present study, the strain-rate sensitivity was reported to be small, implying large activation volumes which would be more consistent with the present results. An earlier study by Lindholm and Yeakley [14] reported the activation volume of 1100 aluminum to decrease from 14 x 10^{-21} cm^3 at 0.5 percent strain to 5 x 10^{-21} cm^3 at 10 percent strain. It appears, however, that their results were calculated from two stress-strain curves obtained at strain rates above and below the value of 0.3 sec^{-1}; the latter value was reported by Holt et al. [13] to be the rate which separates the regions of differing strain rate sensitivity of 1100 aluminum. As a result it is likely that the activation volumes reported by Lindholm and Yeakley [14] are too small in the low strain rate region. Further evidence for this is obtained from recent data by

Dotson [15] on the strain-rate sensitivity of the 0.2 percent offset yield stress of 1100-O aluminum obtained at low strain rates, which indicates a higher activation volume than reported by Lindholm and Yeakley. The magnitude of the strain-rate sensitivity of the flow stress obtained by Dotson [15] can be directly compared with the data obtained for the plasma-sprayed aluminum as shown in Table V, and the general agreement indicates the same strain rate sensitivity for the two materials at low strains. The two materials differ however in that the activation volume decreases with strain in 1100 aluminum [14], consistent with a dislocation intersection mechanism. In contrast, the activation volume is independent of strain in the case of the plasma-sprayed aluminum, suggesting dislocation-particle interactions as the yield controlling mechanism. This result is consistent with the increased strength of the plasma sprayed aluminum due to the presence of the oxide particles.

Kelly [16] has treated the flow stress of a discontinuous fiber composite where the fibers are elastic and the matrix is strain-rate sensitive. He shows that the composite flow stress is very sensitive to the matrix strain-rate exponent in the discontinuous fiber case. For long elastic fibers the flow stress of the composite is related to the flow stress of the matrix through the usual rule of mixtures expression. The strain-rate exponent m in Kelly's study is related to the activation volume, V*, measured in the present work by

$$m = \frac{\sigma}{kT} V^* \qquad (2)$$

where: σ = stress, k = Boltzman constant and T is absolute temperature.

There is relatively little data in the literature concerning the strain-rate sensitivity of composites. Hoover and Allred [4] concluded that the

nonlinearity observed in the applied stress intensity versus midspan deflection curves of plasma sprayed Borsic aluminum composites were the result of strain-rate sensitive matrix yielding, a conclusion supported by the present study. Activation volume data can be interpreted in terms of dislocation interaction models. Additional activation volume measurements on composites could be used in conjunction with matrix data to provide information concerning possible changes in matrix deformation modes introduced by the fibers.

4.3. Poisson's Ratio

The anisotropy of the plasma sprayed aluminum is demonstrated by the Poisson's ratio measurements. Poisson's ratio in Borsic aluminum composites prepared by plasma spraying has been measured only for transverse strains perpendicular to the pressing direction [6]. From this composite data, the *in situ* plastic Poisson's ratio for the matrix was determined to be 0.40. This value is in good agreement with the value of 0.41 obtained for corresponding directions in the present study for the unreinforced, plasma-sprayed aluminum. The agreement indicates that the presence of the fibers in the composites did not perturb the matrix flow enough to obscure the anisotropic nature of the plasma sprayed material.

5. CONCLUSIONS

1. The yield and ultimate tensile strengths of this densified plasma-sprayed aluminum are intermediate between those of 1100-0 aluminum and sintered aluminum powder of similar oxide content.
2. The strength of plasma-sprayed aluminum can be influenced by varying the hot pressing conditions.

3. Variation in the ductility of the plasma sprayed aluminum was accompanied by a change in fracture mode. This was attributed to differences in the atmosphere present during hot pressing.
4. The strain-rate sensitivity of plasma-sprayed aluminum at low strains was similar to that of 1100 aluminum and correlates with the strain-rate sensitivity reported for Borsic-aluminum composites.
5. The activation volume for deformation of the plasma sprayed aluminum was independent of strain, suggesting a dislocation-particle intersection mechanism.
6. The plasma-sprayed aluminum is anisotropic, resulting in an orientation-dependence of Poisson's ratio in the region of plastic strain. The Poisson's ratio measured for the unreinforced matrix is in good agreement with that derived from composite data for the *in situ* matrix.

ACKNOWLEDGMENT

The authors wish to acknowledge the assistance of T. F. Covert, L. E. Hermesmeyer, J. Mata, and J. K. Maurin in carrying out the experimental aspects of this work. In addition we thank W. R. Hoover and M. M. Karnowsky for their review of the manuscript and helpful discussions.

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TABLE I

Plasma-Spraying Conditions Used for the Manufacture of 1100 Aluminum

Powder	- Metco 54 Aluminum (1100 alloy) +400 -170 mesh
Gases	- Arc gas - argon - 1.1 m^3/hr - Powder gas - argon - 0.7 m^3/hr - Cover gas - argon
Gun	- Plasmadyne SG-1B - Electrodes - tungsten and copper - Rear powder feed using a standard hopper
Power Settings	- Plasmadyne control panel - Open circuit voltage - 80 volts - Power control - 19 volts - Operating voltage - 30 volts

Spray stand-off distance - 12.7 cm

TABLE II

Nominal Chemical Analysis of Metco 1100 Aluminum Powder

Element	Concentration, Weight Percent
Cu	<0.001
Fe	<0.28
Si	<0.073
Ti	Trace
Mn	<<0.029
Mg	<0.001
Zn	ND*
Cr	ND*
Ni	ND*
Be	ND*
Pb	ND*
Bi	ND*
Co	ND*
Sn	ND*
O	0.2 ± 0.02%

* ND - Not Detected

TABLE III

Fabrication Conditions

Plate No.	Pressing Temp °C	Reduction in Thickness Percent	Pressing Time min.	Time Between Bagging and Pressing	Oxide Content Wt. Percent Al_2O_3	Room Temp. Yield Strength MPa	Room Temp. Ductility Percent
1	538	50	5	15 min	0.65	53.1	20-30
2	538	63	5	15 min	0.70	56.5	20-30
3	510	50	5	3 weeks	0.91	57.9	4-8
4	538	50	5	3 weeks	0.68	54.5	4-8
5	566	50	5	3 weeks	1.19	52.4	4-8
As Sprayed	-	-	-	-	0.98	-	-

TABLE IV

Comparison of Room Temperature Properties

	Yield Strength MPa	Ultimate Tensile Strength MPa	Elongation Percent
1100-0 Aluminum [Ref. 19]	35	97	40
Plasma Sprayed Aluminum	48-55	97-110	4-30
Sintered Aluminum Powder (SAP) [Ref. 8]	83-117	152-186	25-32

TABLE V

Strain-Rate Sensitivity of 1100 and Plasma Sprayed Aluminum

Temp °C	Increase in yield stress(kPa) for $\dot{\epsilon}_1/\dot{\epsilon}_2 = 10$	
	1100 Aluminum (Ref. 15)	Plasma Sprayed Aluminum
25	1930	820
65	-	960
121	827	-
150	-	1660
177	2760	-
260	-	3102

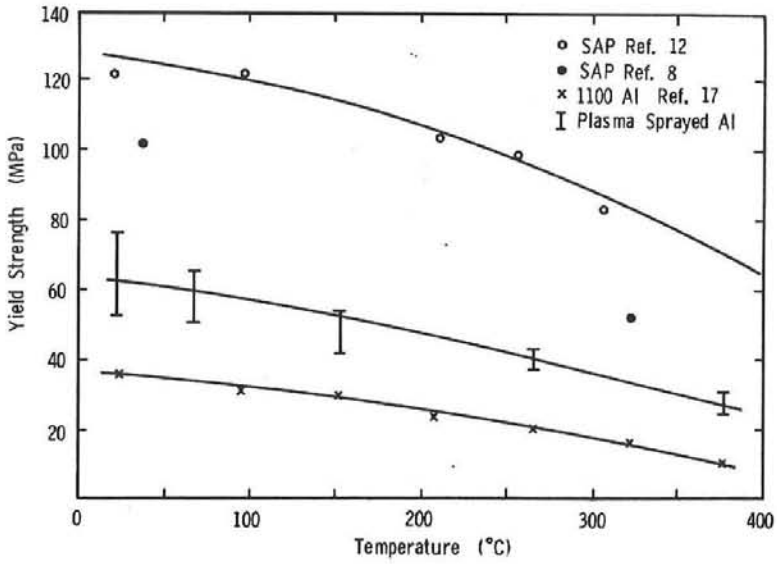

Figure 1. Yield Strength versus Temperature

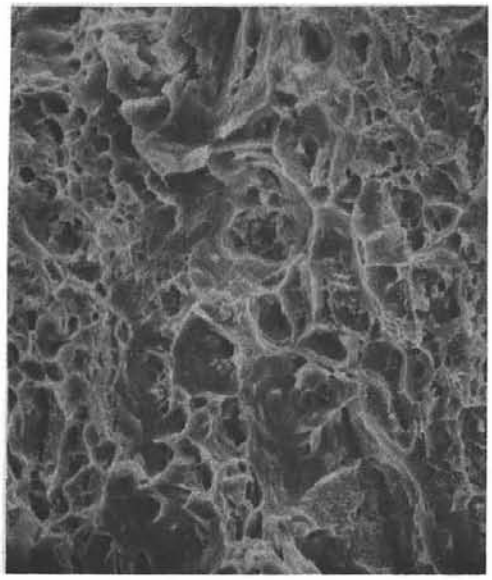

Figure 2a

Scanning Electron Micrograph of the fracture surface of a ductile specimen of plasma sprayed aluminum. 600X

Figure 2b

Scanning Electron Micrograph of the fracture surface of a brittle specimen of plasma sprayed aluminum. 600X

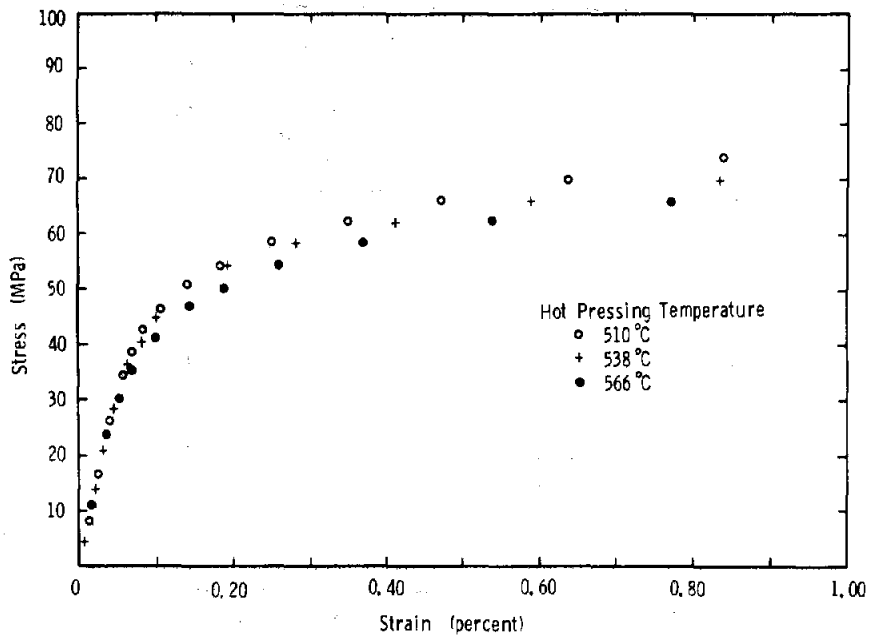

Figure 3. Stress-Strain Curves for Plasma Sprayed Aluminum.

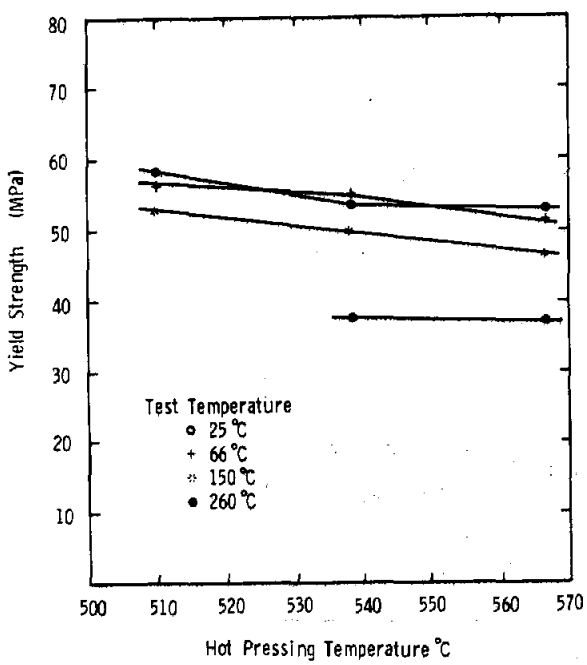

Figure 4a

Variation of yield strength of plasma sprayed aluminum with hot-pressing temperature.

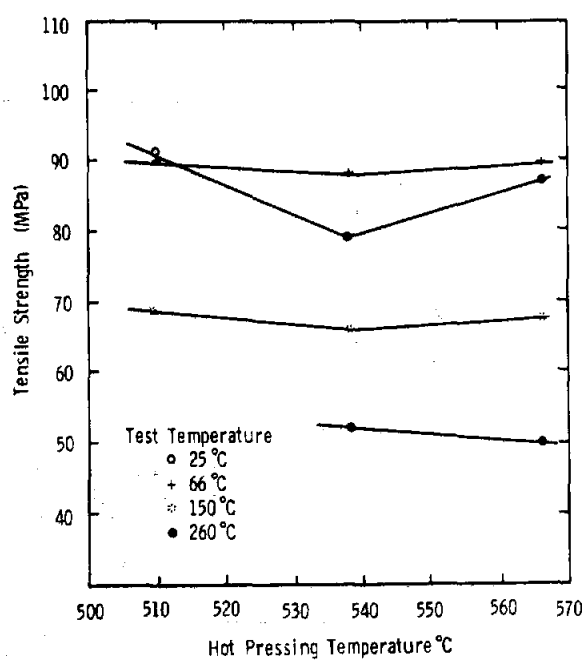

Figure 4b

Variation of tensile strength of plasma sprayed aluminum with hot-pressing temperature.

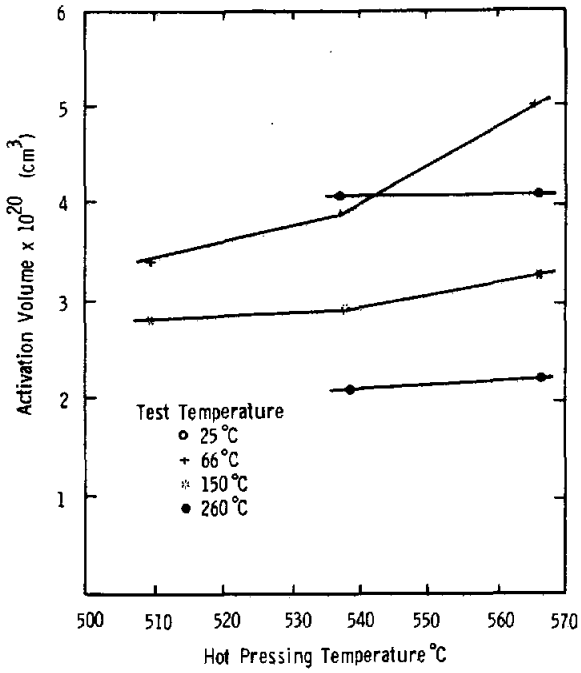

Figure 5. Variation of activation volume of plasma sprayed aluminum with hot pressing temperature.

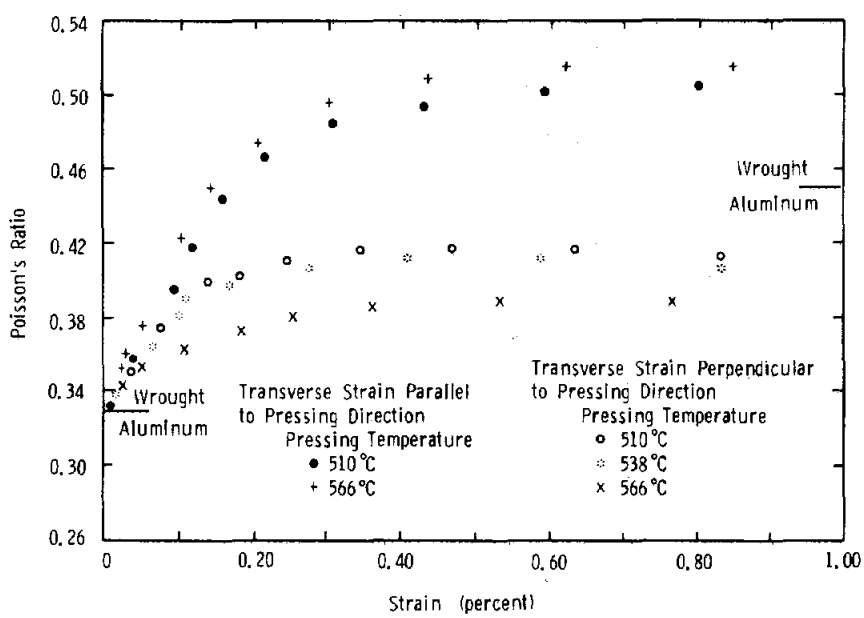

Figure 6. Poisson's ratio of plasma sprayed aluminum as a function of strain.

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