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ABSTRACT

Two commercial oxide dispersion strengthened (ODS) alloys, MA-753 and MA-754, and three experimental ODS alloys, MA-757E, MA-755E, and MA-6000E, were tested in shear at 760° C. Comparisons were made with other turbine blade and vane alloys. All of the ODS alloys exhibited less shear strength than directionally solidified Mar-M 200 + Hf or then conventionally cast B-1900. The strongest ODS alloy tested, MA-755E, was comparable in both shear and tensile strength to the lamellar directionally solidified eutectic alloy $\gamma/\gamma' - \delta$. Substantial improvements in shear resistance were found for all alloys tested when the geometry of the specimen was changed from one generating a transverse tensile stress in the shear area to one generating a transverse compressive stress. Finally, 760° C shear strength as a fraction of tensile strength was found to increase linearly with the log of the transverse tensile ductility.

INTRODUCTION

In addition to severe tensile stresses, materials employed as gas turbine blades are subject to a variety of other stresses, including shear stresses. Candidate materials for advanced blade application include oxide dispersion strengthened (ODS), directionally solidified (DS) eutectic, and refractory fiber reinforced alloys. In each of these advanced alloy systems, a longitudinal alignment of microstructural elements (fig. 1) contributes enhanced high temperature creep strength. But this alignment provides a potentially easy path for shear failure.

The tensile and creep shear properties of a DS eutectic alloy, $\gamma/\gamma' - \delta$, have already been reported (refs. 1 and 2). The objective of this study was to determine the tensile shear strengths of several ODS alloys at 760° C. Comparisons were made with DS eutectic alloys and currently used directionally and conventionally cast turbine blade alloys. No comparable data were available for fiber reinforced alloys.

MATERIALS

Nominal compositions of the alloys used in this program are listed in table I. The ODS alloys cover a range from the simple solid solution alloy MA-754, to the more complex gamma prime precipitation strengthened alloys MA-755E and MA-6000E. The suffix E applied to three of the ODS materials is indicative of their experimental status. MA-6000E is a particularly recent development identified as alloy D in reference 3. The alloys MA-755E and MA-6000E are strengthened by refractory metal solid solution additions as well as by gamma prime precipitates and the oxide dispersion; they may be considered as candidates for advanced gas turbine blade application. The alloys MA-754, MA-753, and MA-757E have neither refractory metal additions nor substantial volume fractions of gamma prime. Thus, they have less strength at intermediate temperatures and are more likely to be used as vanes (MA-754 is in fact already in service as a vane material). All the ODS alloys tested were made by the mechanical alloying process (ref. 4). The fabrication sequence of ODS alloys MA-753, MA-754, and MA-757E included both extrusion and hot rolling; the alloys MA-755E and MA-6000E were extruded but not further worked by rolling. At the time of this study, hot rolled MA-6000E of sufficient thickness (1.2 cm) for shear testing was not available. Conventionally cast B-1900 and DS Mar-M 200 + Hf were chosen to represent materials currently used as gas turbine blades. Samples of a nickel-based DS single crystal superalloy, Mar-M 247, were tested in shear while literature data was examined for a new DS eutectic alloy, γ/γ' - Mo. A few well aligned samples of the lamellar DS eutectic alloy γ/γ' - δ were also available for test.

PROCEDURE

Two types of shear specimens (figs. 2(a) and (b)) and a conventional tensile specimen (fig. 2(c)) were used in this program. The first specimen (fig. 2(a)) was similar to that used successfully for shear testing DS eutectic alloys (refs. 5 and 6). For this study the specimen head was locally reduced in thickness to decrease the shear area. This modification was required to avoid tensile failures in the specimen shaft. While this specimen was designed to test shear strength, the stress state in the failure area included both longitudinal shear and transverse tensile stresses. A second type of specimen (fig. 2(b)) was fabricated which could be tested by compressive rather than tensile loading. In this case, the stresses in the shear failure area included longitudinal shear and transverse compression. In both cases described above the transverse stresses were generated by differential expansion or contraction of the specimen shaft relative to the specimen head. The differential strains were caused by Poisson ratio effects as illustrated in figure 3.

All shear and tensile testing was conducted in air at 760° C. This temperature was chosen as representative of advanced gas turbine engine blade root temperatures. The crosshead speed for both shear and tensile testing was 0.025 cm/min; for tensile testing this corresponded to an initial strain rate of 0.01/min. Specimens were examined after failure by standard metallographic techniques including scanning electron microscopy.

RESULTS

Microstructures

Shear fractures in the ODS alloys tested with superimposed transverse tension (specimen of fig. 2(a)) occurred primarily along grain boundaries. Typical transverse views of shear failures are shown in figure 4. Longitudinal views are shown in figure 5; included is a sample of $\gamma/\gamma' - \delta$ showing the very straight fracture path typical of this alloy. When shear tests were conducted with superimposed compressive stress (specimen of fig. 2(b)) the fracture path was independent of the location of grain boundaries (fig. 6). There was very little plastic deformation evident for any of the materials tested in either shear manner.

Mechanical

The 760° C shear with transverse tensile stress, shear with transverse compressive stress, and tensile strength data obtained in this study are listed in table II. Data for the DS eutectic alloy presented in table II, columns 1 and 3, were taken from reference 1. For convenience, the results are listed in both engineering and metric units. It may be noted, that none of the ODS alloys tested had shear strengths as high as that of DS Mar-M 200 + Hf. The two blade candidate ODS alloys tested, MA-755E and MA-6000E, had shear strengths approximately equivalent to that of $\gamma/\gamma' - \delta$. When the transverse stress was compressive, table II, column 2, the measured shear strength for all alloys was greatly increased, generally by a factor of two, as compared to the shear tests with transverse tensile stress, table II, column 1. There was a fair degree of scatter in all the tests, but especially in the tests with transverse compression added to shear stress. Some of this scatter may be attributed to the absence of an alignment fixture in the compressive load train.

The level of ultimate tensile strength of the alloys tested when considered alone gave no indication of the shear strength. In figure 7, the shear strengths determined with specimen 2a, the specimen with a superimposed transverse tensile stress, are displayed as fractions of corresponding tensile strengths. The ratios for alloys tested varied from 0.3 for $\gamma/\gamma' - \delta$ to 0.6 for MA-754. The value of 0.7 for cast B-1900 was determined from data in references 1 and 7. For the ODS alloys the higher ratios are for the alloys MA-753, MA-754, and MA-757E; these alloys were fabricated by extrusion followed by rolling. The ODS alloys fabricated by extrusion alone show a lower ratio of shear to tensile strength. While the shear strength did not correlate well with tensile strength alone, examination of the 760° C tensile strength in conjunction with the 760° C transverse tensile ductility from reference 8 did yield an interesting correlation (table III). The ratio of shear (specimen 2a) to tensile strength was plotted as a function of the reduction in area of specimens tensile tested transversely to any microstructural alignment (fig. 8). For materials of this study and additional materials (refs. 10 and 11) the increase in shear to tensile ratio was approximately linear with the logarithm of transverse ductility (% RA). The data for figure 8 represent a wide variety of materials including a conventionally cast superalloy, a single crystal superalloy, a DS superalloy, two distinctly different DS eutectic alloys and ODS alloys further strengthened by volume fractions of gamma prime ranging from nil to 55v/o. There was no evident correlation between shear strength and the ductility of longitudinally oriented specimens. Assuming the demonstrated relation was valid, the 760° C shear strength of hot rolled MA-6000E (not yet determined) was calculated from longitudinal tensile strength and transverse reduction in area data (ref. 8). The calculated result for hot rolled MA-6000E was 480 MPa(70 KSI), a considerable improvement over the 285 MPa(41.4 KSI) shear strength of the MA-6000E of this investigation fabricated by extrusion alone.

DISCUSSION

The generally low values of shear strength measured for the ODS alloys indicate that special care must be taken if they are to be used as gas turbine blades. The suggestion, already made for the $\gamma/\gamma' - \delta$ system (ref. 2), that the highly stressed blades might incorporate a root section of a conventional superalloy is also appropriate for the ODS materials tested in this study. It is possible that mechanical treatments, such as hot rolling or forging may provide the requisite improvement in shear strength; or it may be possible to design blade root attachments sufficiently different from current concepts to accommodate materials of lower shear strength.

It is important to note that the shear capability is strongly affected by the total stress state. The shear stress at failure was much greater for the specimen geometry with a superimposed transverse compressive stress than for the specimen generating a transverse tensile stress. In a blade root the areas of highest shear stress also experience a considerable transverse compressive stress (ref. 2). The origin of the transverse compressive stress is illustrated in figure 9. Neither of the shear specimens used in this study simulated well the total stress state in a real blade root. It is recommended that in future studies the test specimen resemble more closely the geometry of the intended application. In addition, the effect of time on shear load carrying capability should be determined.

It was noted that those ODS alloys which were processed by both extrusion and warm rolling had higher ratios of shear to tensile strength than those which were fabricated by extrusion alone. While this disparity may be due to other factors, such as, differing gamma prime contents, improved shear capability may result when post extrusion working is included in the fabrication of such alloys as MA-6000E. The anticipated commercial practice does include hot rolling. It has already been shown that hot rolled MA-6000E has substantially higher transverse tensile ductility (3.2% RA, ref. 8) than the comparable extruded alloy MA-755E (0.3% RA, ref. 8). And if the relationship of figure 8 holds, its shear strength may be expected to be higher too, comparable to that of DS Mar-M 200 + Hf.

Finally, although there was little or no plastic deformation metallographically evident for any of the shear tested specimens, the strong mathematical dependence on ductility attests to the importance of plastic accommodation for the attainment of superior shear strength. Because the increase in ratio of 760° C shear to tensile strength was approximately linear with the log of transverse reduction in area small improvements in the ductility of low ductility alloys may be expected to be more beneficial to shear strength than equal improvements in alloys of higher original ductility.

SUMMARY AND CONCLUSIONS

Several oxide dispersion strengthened alloys were tested at 760° C in shear and tension. Comparisons were made with the directionally solidified eutectic alloys $\gamma/\gamma' - \delta$ and γ/γ' - Mo, with two currently used gas turbine blade materials, directionally solidified Mar-M 200 + Hf and conventionally cast B-1900, and with a directionally solidified single crystal superalloy, Mar-M 247. The following conclusions are based on short time tests only; for turbine blade applications creep shear results must also be obtained and considered.

1. None of the ODS alloys tested, including two of the type considered for turbine blade application, had shear strength as high as that of DS Mar-M 200 + Hf or of B-1900. The shear strength of the stronger ODS alloys fabricated by extrusion was about the same as that of $\gamma/\gamma' - \delta$, too low for highly stressed turbine blade dovetails. It was suggested that to use an extruded ODS superalloy a modified root design or a composite blade having a ODS alloy airfoil and a more conventional superalloy root portion may be required.

2. Stresses other than shear imposed on the shear failure area greatly affected the measured shear resistance. When the specimen design was such that significant transverse compressive stresses were added, the measured shear strength was much higher than when transverse tensile stresses were added.

3. By examining data for diverse superalloys an empirical relationship between the ratio of 760° C longitudinal shear to tensile strength and the transverse tensile ductility was discovered. The increase in shear to tensile ratio was approximately linear with the logarithm of transverse ductility measured as reduction in area. Therefore, small improvements in the ductility of low ductility alloys may be expected to be much more important to increased shear capability than equal improvement in alloys to higher initial ductility.

4. From the measured longitudinal tensile strength and transverse tensile ductility of an ODS superalloy, MA-6000E, processed by hot

rolling its shear strength was calculated to be equivalent to that of DS Mar-M 200 + Hf. It thus appears possible that the shear strength of ODS superalloys can be improved sufficiently by thermomechanical working to allow their use in the root portion of gas turbine blades.

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TABLE I. ALLOYS EXAMINED IN THIS INVESTIGATION.

Alloy	Ni	Cr	W	Mo	Ta	Ti	Al	Other	Fabrication
MA-753	Bal	20.3	----	----	---	2.7	1.5	$1.4Y_2O_3$	Extrusion plus warm working
MA-754		20.2	----	----	---	0.4	0.3	$0.6Y_2O_3$	
MA-757E		15.8	----	----	---	0.6	3.9	$0.7Y_2O_3$	
MA-755E		15	5.5	3.5	2.5	2.5	4.5	$1.1Y_2O_3$	Extrusion
MA-6000E		15	4	2	2	2.5	4.5	$1.1Y_2O_3$	
DS Mar-M 200 + Hf		9	12.5	----	---	2	5	10Co,1Cb,2 Hf	Directional solidification
DS γ/γ' - δ		6	----	----	---	---	2.8	20.1Cb	
DS γ/γ' - Mo		----	----	32.3	---	---	5.7	------	
DS Mar-M 247		8.4	10.1	0.7	3	1	5.5	10.3Co,1.5 Hf	
B-1900		8	----	6	4	1	6	10Co	Conventionally cast

TABLE II. 760° SHEAR AND TENSILE DATA

Alloy	Shear Strength, Specimen 2a, KSI	Shear Strength, Specimen 2a, MPa	Shear Strength, Specimen 2b, KSI	Shear Strength, Specimen 2b, MPa	Tensile Data U.T.S. KSI	Tensile Data U.T.S. MPa	Tensile Data Elong %
MA-753	37.9	261	101.5	700	85.2	587	6
MA-753	37.7	260	83.7	577	84.7	584	6
MA-753	----	---	-----	---	81.7	563	7
MA-754	24.8	171	45.1	311	43.8	302	22
MA-754	26.8	185	55.1	380	44.4	306	24
MA-754	----	---	44.4	306	-----	-----	---
MA-757E	45.6	314	84.7	584	81.4	561	7
MA-757E	43.8	302	73.3	505	79.8	550	9
MA-757E	----	---	75.2	519	-----	-----	---
MA-755E	46.5	321	98.1	676	131.8	909	1
MA-755E	46.6	321	118.5	817	126.2	870	1
MA-755E	----	---	109.4	754	-----	-----	---
MA-6000E	41.6	287	94.1	649	129.9	896	6
MA-6000E	43.0	296	103.9	716	129.0	889	6
MA-6000E	39.6	273	-----	---	-----	-----	---
DS Mar-M 200 + Hf	69.9	482	158.9	1096	147.1	1014	12
DS Mar-M 200 + Hf	64.5	445	172.8	1191	156.2	1077	18
DS Mar-M 200 + Hf	66.0	455	-----	----	-----	-----	---
DS Mar-M 200 + Hf	69.1	476	-----	----	-----	-----	---
DS $\gamma/\gamma' - \delta$	44[1,2]	303[1,2]	103.8	716	161[1]	1110[1]	11[1]
DS $\gamma/\gamma' - \delta$	-----	-----	100.8	695	-----	-----	---
DS $\gamma/\gamma' - \delta$	-----	-----	132.4	913	-----	-----	---
DS Mar-M 247,	85.9	592	-----	---	151[3]	1041[3]	11[3]
Single Crystal	94.3	650	-----	---	-----	-----	---
DS γ/γ' - Mo	89.6[2,4]	618[2,4]	-----	---	159[4]	1099[4]	17[4]
B-1900	97[1,2]	669[1,2]	-----	---	138[5]	952[5]	4[5]

1. Ref. 1.
2. Iosipescu specimen, pure shear.
3. Ref. 10.
4. Ref. 11.
5. Ref. 7.

TABLE III. LONGITUDINAL SHEAR STRENGTH, LONGITUDINAL TENSILE STRENGTH, RATIO OF SHEAR TO TENSILE STRENGTH, AND TRANSVERSE TENSILE DUCTILITY FOR SEVERAL ALLOYS TESTED AT 760° C

Alloy	Shear Strength, Specimen 2a, MPa	Tensile Strength, MPa	Ratio Shear Tensile	Transverse RA, %
MA-753	261	578	0.45	0.7[1]
MA-754	178	304	0.59	7.5[1]
MA-755E	321	889	0.36	0.3[1]
MA-6000E				
Extruded only	285	892	0.32	N.A.[2]
Hot Rolled	N.A.[2,3]	1000	N.A.[2,4]	3.2[1]
DS Mar-M 200 + Hf	464	1045	0.44	2.6[5]
DS $\gamma/\gamma' - \delta$	303[6,7]	1110[6]	0.27	0.3[5]
DS $\gamma/\gamma' - \delta$, Optimized	384[6,7]	1110[8]	0.35	0.8[5]
DS γ/γ' - Mo	618[7,9]	1099[9]	0.56	17[9]
DS Mar-M 247, Single Crystal	621	1041[10]	0.60	11[10]
B-1900	669[6]	952[11]	0.70	15[12]

1. Ref. 8.
2. Not available.
3. Estimated from figure 8 as 480 MPa.
4. Estimated from figure 8 as 0.48
5. "Failure Strain," ref. 1.
6. Ref. 1.
7. Iosipescu specimen, pure shear.
8. Assumed same as $\gamma/\gamma' - \delta$.
9. Ref. 11, Test temperature 750° C.
10. Ref. 10.
11. Ref. 7.
12. Ref. 9, Interpolated.

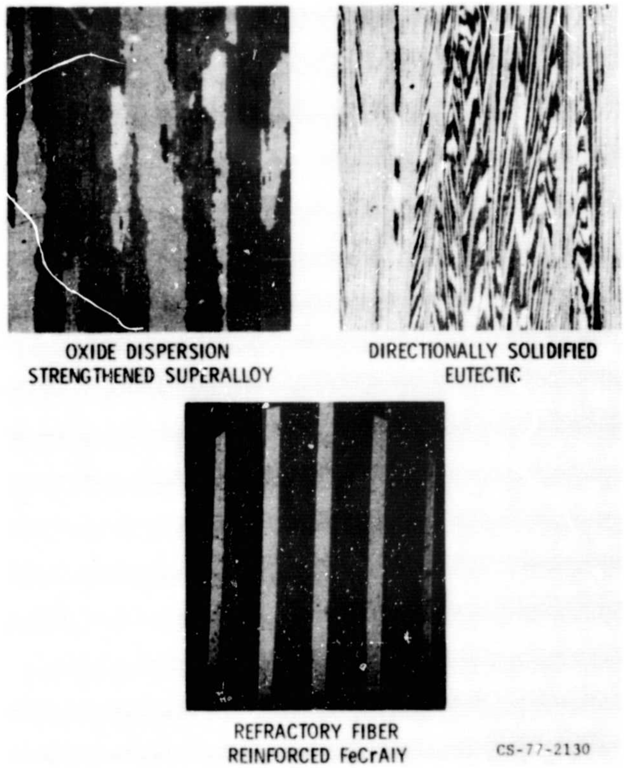


Figure 1. - Competitive materials for advanced turbine blades with elongated microstructures for improved creep strength.

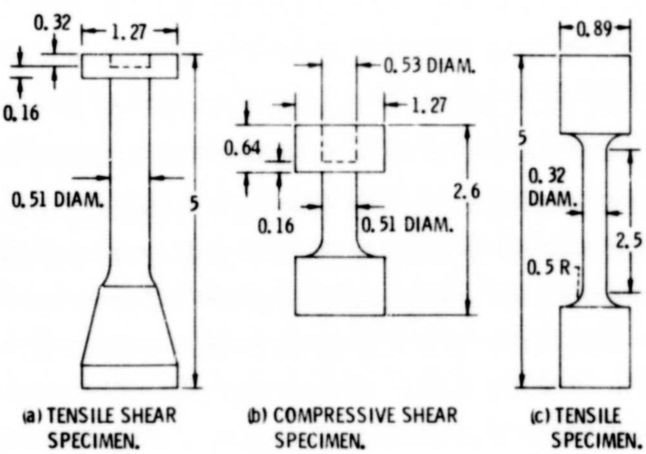


Figure 2. - Test specimens used in program; all dimensions in cm.

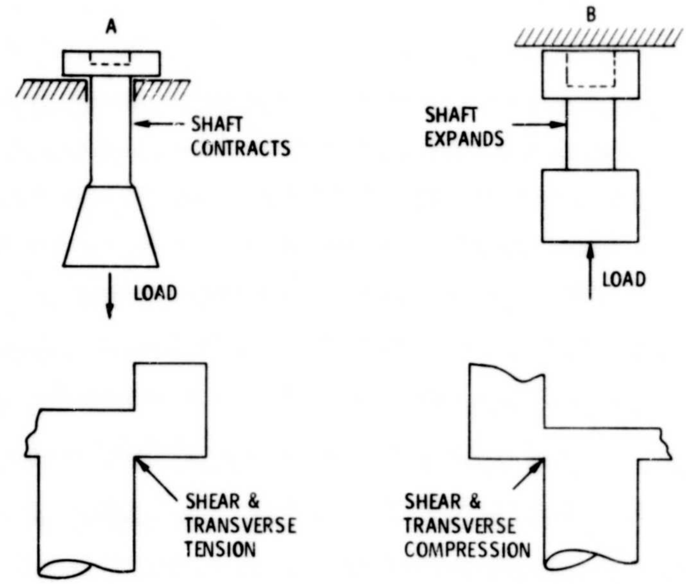


Figure 3. - Poisson's ratio effects cause transverse stresses during shear testing.

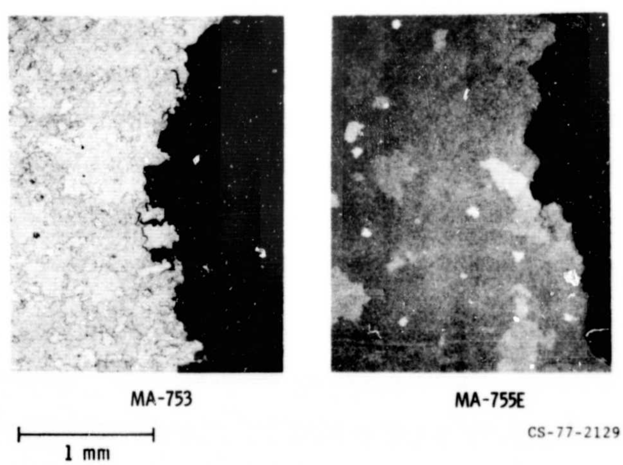


Figure 4. - Shear failures of tensile shear specimens along grain boundaries, transverse views.

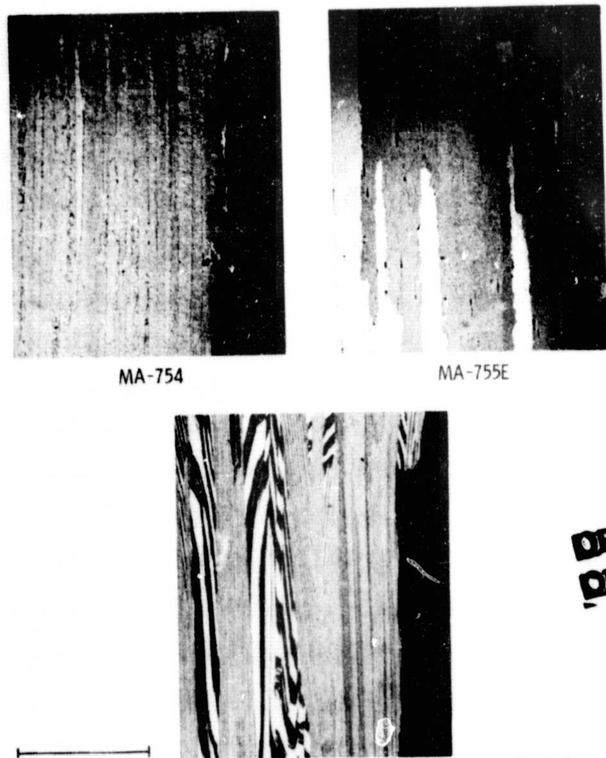
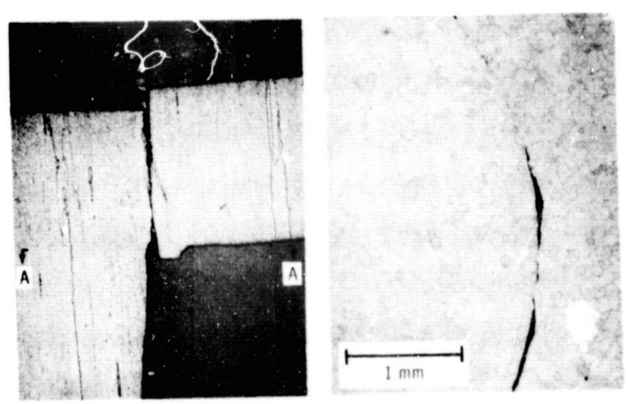


Figure 5. - Shear failures of tensile shear specimens, longitudinal views.



(a) LONGITUDINAL VIEW, MA-6000E. (b) TRANSVERSE VIEW, AS IN SECTION AA, MA-753.

Figure 6. - Shear failures under combined shear and compressive stresses, independant of grain boundary position.

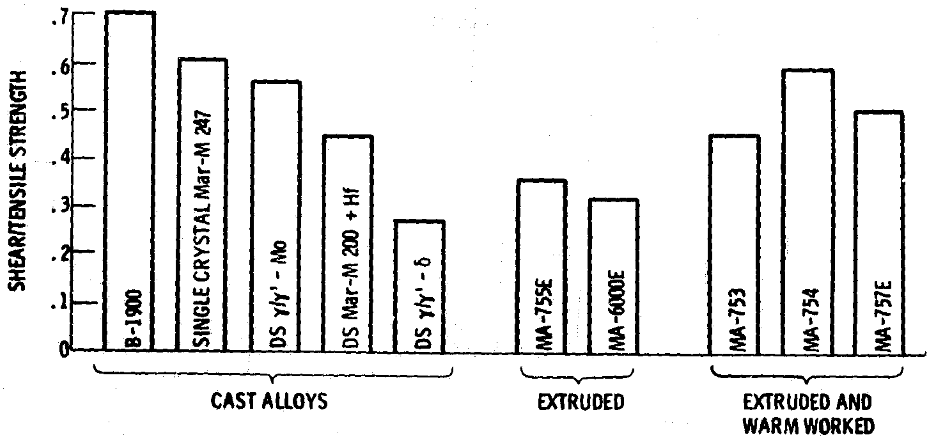


Figure 7. - Ratio of shear (specimen 2a) to tensile strength at 760° C.

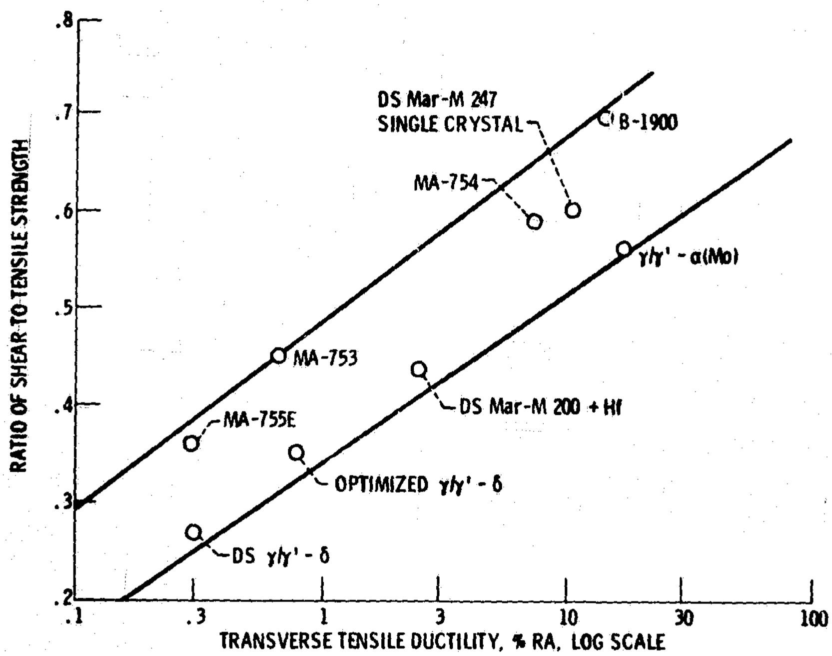


Figure 8. - Relation between the ratio of 760° C shear strength to ultimate tensile strength and transverse tensile ductility.

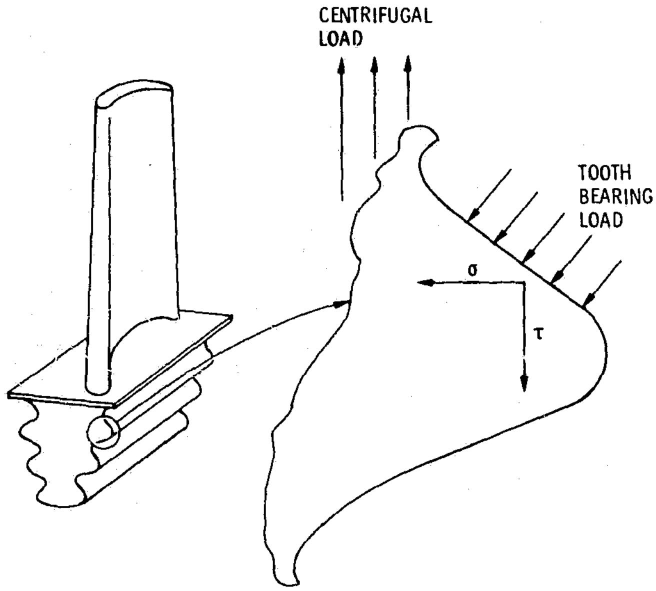


Figure 9. - The centrifugal load on a gas turbine blade is resisted by the tooth bearing load. The tooth load may be resolved into two components, a compressive stress, σ, acting perpendicular to the blade axis, and a shear stress, τ, acting parallel to the blade axis.