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EFFECT OF CASTING GEOMETRY ON MECHANICAL PROPERTIES OF TWO NICKEL-BASE SUPERALLOYS

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16. Abstract
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EFFECT OF CASTING GEOMETRY ON MECHANICAL PROPERTIES OF TWO NICKEL-BASE SUPERALLOYS

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SUMMARY

An investigation was performed to determine mechanical properties of two rhenium-free modifications of alloy TRW-NASA VIA to evaluate the suitability of the alloy for use in a small integrally cast turbine rotor. The two alloys (TRW-R and TRW-S), which differ from each other by having small variations in carbon and in reactive and refractory metals, were initially developed using stress rupture properties of specimens machined from solid gas turbine blades. Properties in this investigation were determined from cast-to-size bars and bars cut from 3.8 by 7.6 by 17.8 centimeter blocks. Specimens machined from blocks usually had inferior tensile strength and always had markedly poorer rupture lives than cast-to-size bars. At about 1000° C the cast-to-size bars had shorter rupture lives than those machined from blades. Alloy R generally had better properties than alloy S in the conditions evaluated. The results show the importance of casting geometry on mechanical properties of nickel-base superalloys and suggest that the geometry of a component be simulated when developing alloys for the component.

INTRODUCTION

Nickel-base superalloys have been developed to the point where they can be used as structural elements at about 75 percent of the melting point of nickel. The alloys have usually been developed using mechanical properties obtained from cast-to-size (CTS) test samples having a gage diameter of about 0.64 centimeter (cm).

The development of air-cooled turbine airfoils having thin cross sections for aircraft gas turbines renewed activity in studying the effect of casting section size on the mechanical properties of superalloys. It was recognized that most mechanical proper-

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ties degrade as the section size decreases from 0.64 cm to cooled airfoil thicknesses of 0.038 cm (refs. 1 and 2).

In an effort to improve a previously defined alloy (TRW-NASA-VIA) by lowering the cost and density and improving the ductility, Collins (ref. 3) elected to use stress rupture data from specimens machined from a solid blade for a commercial aircraft gas turbine. This allowed the mechanical properties used for the alloy development to more nearly represent those in the final application than would CTS material. Collins identified two rhenium-free modifications of TRW-NASA-VIA, designated TRW alloy R and TRW alloy S, which appeared to have improved stress rupture properties compared to alloy VIA in blade section size.

The investigation reported here was initiated to evaluate mechanical properties of alloys R and S cast into 0.64 cm bars and in a section size simulating the hub of a small integrally cast turbine rotor.

Tensile strength was determined from room temperature to 1000° C and rupture lives were measured from 760° to 1040° C.

MATERIALS AND PROCEDURES

Casting

A two-step casting procedure was employed for each alloy. In the first step, ingots were prepared in a vacuum induction melting furnace using virgin charges with the alloying constituents being of the quality normally used for cast aircraft parts. The charge weight was 32 kilograms. Chemical analyses were performed on an X-ray fluorescence analyzer, and the results are presented in table I for the two alloys. These results showed the alloying element boron to be somewhat higher than the aim, titanium to be somewhat lower for both alloys, and zirconium to be somewhat higher for alloy R. Based on previous experience with these alloys, these deviations from the aim chemistry were judged not to have a significant effect on the mechanical properties.

In the second step, the ingots were remelted in a vacuum induction furnace and conventionally cast into either 0.64-cm-diameter standard aircraft quality control specimens (fig. 1(a)) or a 3.8 by 7.6 by 17.8 cm block (fig. 1(b)). Three clusters of 16 specimens and one block were cast for each alloy. All specimens and blocks were visually inspected and radiographed. They were found free of casting defects.

Specimen Preparation

The CTS specimens and blocks were given a heat treatment of 930° C for 16 hours and air cooled prior to machining. Sixteen test specimens were cut and machined from the cast block. The blocks were cut in a manner such that no test bar had a gage section directly under the riser. Both CTS and machined-from-block (MFBK) specimens were machined to the dimensions shown in figure 2.

Mechanical Testing Procedures

Mechanical property testing included both tensile and stress rupture tests. The CTS specimens were tensile tested at room temperature, 500°, 650°, 750°, 870°, and 1000° C. They were stress rupture tested at the following conditions ($^{\circ}$C/MPa): 760/655, 760/621, 890/414, 890/276, 1000/276, 1000/172, and 1040/172. The MFBK specimens were tensile tested at 550°, 650°, 750°, and 870° C. They were stress rupture tested at the following conditions ($^{\circ}$C/MPa): 760/655, 760/621, and 890/276. Testing was conducted in air and in accordance with ASTM standards. A minimum of two tests was run at each test condition.

RESULTS AND DISCUSSION

Tensile Tests

Tensile tests were run at temperatures from room temperature to 1000° C. The data are shown in table II. Figure 3(a) compares the effect of temperature on the average tensile properties obtained from CTS and MFBK specimens of alloy R. The average ultimate tensile strength of the CTS specimens varies with increasing temperature from 1005 megapascals (MPa) at room temperature to 1020 MPa at 650° C; it then decreases to 480 MPa at 1000° C. The average tensile strengths of MFBK specimens are lower than those of CTS specimens and vary from 875 MPa at 550° C to 940 MPa at 750° C. It should be noted in table II that for CTS specimens of alloy R at temperatures to 750° C a large amount of scatter was observed in ultimate strength. The range of ultimate strength values at 550° through 750° C was such that one CTS specimen showed lower strength than at least one MFBK specimen.

The yield strength of the CTS specimens shows trends similar to those observed for the ultimate strength. The maximum average yield strength of 875 MPa occurs at 750° C. The average room temperature yield strength is 860 MPa. At 550°, 650°, and 750° C the average yield strengths of MFB specimens are 100 MPa lower than CTS specimens. The average elongation of all MFBK specimens is slightly greater than for CTS specimens. The variation of elongation with temperature is not judged to be significant.

Data for a different heat of alloy R obtained in a private communication from Mr. Bruce Ewing of Detroit Diesel Allison Division are also shown in figure 3(a). For CTS specimens, it is shown that, except for room temperature ultimate strength, the properties measured in this study are in agreement with Ewing's data.

Figure 3(b) compares the effect of temperature on the average tensile properties of alloy S CTS and MFBK specimens. For the CTS specimens the average ultimate tensile strength varies from 955 MPa at room temperature to 1030 MPa at 650° C. It decreases to 415 MPa at 1000° C. The average yield strength varies from 790 MPa at room temperature to 310 MPa at 1000° C. The elongation varies from 4.5 percent at room temperature to 9.7 percent at 1000° C. For MFBK specimens the average ultimate tensile strengths are 150 to 250 MPa lower than for CTS specimens. The yield strengths for MFBK specimens are from 75 to 140 MPa lower than for CTS specimens. Average CTS elongations are slightly higher than MFBK elongations.

It can be seen by comparing alloys R and S that alloy R generally has greater strength but lower elongation. The comparison between tensile strengths of alloys R and S in figure 4 shows that for the MFBK specimens alloy R is stronger than alloy S at each test temperature from 550° to 870° C. The superiority of alloy R is most marked at the intermediate temperature, 750° C. For CTS specimens the difference between the strength of alloy R and alloy S is small. The yield strength of alloy R was greater than alloy S for both specimen types except at 750° C where that of CTS alloy S was greater.

Stress Rupture Tests

Stress rupture tests were run at temperatures varying from 760° to 1040° C with stresses varying from 655 to 170 MPa. The results are tabulated in table III. Figure 5(a) is a Larson Miller plot for alloy R. In addition to the data from this investigation, data from reference 3 and data obtained in a private communication from Mr. Bruce Ewing of Detroit Diesel Allison are also shown. The curve is drawn for CTS data.

It can be seen that the CTS rupture strength data in this investigation agree well with Ewing's data. At low parameter values (low temperatures) the rupture strengths for CTS specimens are about 35 MPa greater than for MFB specimens and are about the same as those reported by Collins (ref. 3) for specimens machined from blades. At high parameter values, specimens cut from blades (ref. 3) have rupture strengths about 30 MPa greater than CTS specimens.

Figure 5(b) is a Larson Miller plot for alloy S. At low parameter values, the CTS specimen rupture strength is about 30 MPa greater than the MFBK specimen rupture strength and about the same as that of specimens machined from blades (ref. 3). At high parameters, CTS rupture strengths are about 30 MPa weaker than the rupture strengths of specimens machined from blades.

The rupture elongation is generally greater for alloy S than for alloy R (table III). For both alloys CTS specimens have 2 to 3 percent greater elongations than MFBK specimens at 760° C, but they are about equal at 890° C. Figure 6 shows a comparison between alloys R and S on the basis of temperature for a 1000-hour stress rupture life at several stress levels. The temperature for a 1000-hour stress rupture life was estimated from Larson-Miller plots in figure 5. In this comparison, for CTS specimens the temperatures are higher for alloy R. But for MFBK specimens, alloy S has a higher temperature. Alloy S showed less effect due to section size than did alloy R. Also shown in figure 4(b) are CTS data for alloy VIA from reference 4. At high stress conditions (655 and 621 MPa), low temperature alloys R and VIA are equivalent in use temperature; however, at 276 MPa and high temperature, alloy VIA is better than either alloy R or S.

Metallographic Examination

Typical microstructures of CTS and MFBK specimens are shown in figures 7(a) and (b), respectively, for alloy R. The microstructural features of alloy S were essentially the same as those shown for alloy R. The alloys had structures typical of cast nickel-base superalloys consisting of eutectic γ' nodules, blocky γ', and carbides. Both blocky and script shaped carbides were observed in the microstructures. The amount of eutectic γ' nodules was measured by Andrews (ref. 5) to be about 12 volume percent for the alloys in both CTS and MFBK samples.

The major difference noted between the microstructure of the CTS and MFBK materials is the general coarseness of the constituents in the MFBK material. The grain size for the CTS specimens was about 1 millimeter compared to about 6 millimeters for the MFBK specimens. Comparing the two top micrographs of figure 7 shows that the eutectic γ' nodules in the blocks have diameters about five times the diameter of the nodules in the CTS material. The primary dendrite arm spacing in the blocks is about three times that measured in the CTS specimens. The blocky γ' in the CTS specimens has a more rectangular shape than in the MFBK specimens (compare bottom two micrographs). Also, the average diagonal of the block γ' of the CTS specimens is shown to be about one-half that in the blocks. No significant difference in porosity was observed between the CTS and MFBK specimens.

The chemical compositions of various microstructural constituents were analyzed using energy dispersive analyses of X-rays. No significant differences were observed between CTS and MFBK samples nor from alloy R to alloy S. Both the coarse blocky and the script shaped particles were tantalum-rich and to a lesser extent titanium-rich compared to the base alloy. These particles are therefore presumed to be tantalum-base monocarbides (MC). Some of the MC carbides appeared to be enriched in hafnium. The γ' nodules were enriched in nickel, cobalt, and aluminum but depleted in chromium when compared to the base alloy. This is consistent with observations made on nickel-base superalloys reported in the literature.

CONCLUDING REMARKS

This investigation was initiated to evaluate mechanical properties of two modifications of TRW-NASA-VIA, TRW alloys R and S, as CTS 0.64 cm bars and in a section size simulating the hub of a small integrally cast turbine rotor. The alloys selected for evaluation were identified by Collins as having attractive stress rupture properties when cast as turbine blades. No effort was made in this investigation to alter either the compositions or foundry practice used by Collins in his initial studies to optimize properties for the section sizes studied here.

In general, the properties of the MFBK alloys were weaker than CTS specimens and showed no advantage over commercially available alloys which are used for integrally cast turbine rotors. We believe that the cause of the poorer mechanical properties in the block casting is the extreme coarseness of the microstructure, particularly γ' size, when compared to the CTS specimen. It is possible, however, that a modification in foundry practice and perhaps minor alterations in chemistry could improve the thick section properties of these alloys.

The tensile strengths measured in this investigation for the two alloys in the CTS condition are comparable to several advanced Ni-base superalloys, but lower than TRW-NASA VIA. The CTS specimen rupture lives for alloys R and TRW-NASA VIA are equivalent for stresses above 621 MPa and greater than for alloy S. At 276 MPa alloy VIA has a greater rupture life than either alloys R or S.

It is instructive to consider the relation of the strengths of the two section sizes studied here and that of the section size initially evaluated by Collins (ref. 3). The strengths measured in this work were never significantly greater than those reported by Collins for specimens machined from blades. The MFBK strengths were usually inferior to the CTS or machined-from-blade strengths. In other words, these alloys tended to be strongest and have the greatest stress rupture lives in the thinner section sizes. This is in contrast to the findings in reference 2 where rupture lives were greatest for the thickest section sizes and strengths were usually greater for the largest section size. Similarly, in reference 1 (fig. 19) Collins shows a general decrease in rupture life with decreasing section thickness. However, Collins further noted that the thin section stress rupture lives can be improved by controlling grain size and alloy composition.

The authors had expected that the MFBK specimen properties would likely be poorer than the properties of CTS specimens. However, the stress rupture lives of the materials tested here were particularly disappointing. We believe that these results might have better been anticipated by considering that Collins developed alloys R and S for application to very thin section air-cooled airfoils. He was attempting to optimize the alloys' chemistries for the foundry practice associated with that particular casting geometry and section size. On the other hand, the alloys studied in reference 2 were probably developed using 0.64-centimeter test bars. In both cases one might expect that the best properties will be found in the section size used to develop the composition and that deviations from that size and geometry, thicker or thinner. might result in property degradation. We believe that the results show the importance of casting geometry on mechanical properties of nickel-base superalloys and suggest that the geometry of a component be simulated when developing alloys for that component.

SUMMARY OF RESULTS

An investigation was conducted to determine the mechanical properties of two nickel-base alloys in 0.64-centimeter cast-to-size (CTS) bars and in bars cut from 3.8 by 7.6 by 17.8 cm cast blocks. All materials were aged 16 hours at 927° C prior to being tested. The alloys, designated R and S, are rhenium-free derivatives of alloy TRW-NASA VIA and differ by small variations in carbon and reactive and refractory metals. Comparisons were made between CTS and machined-from-block (MFBK) specimens and in some cases with previously reported properties of specimens cut from turbine blade airfoils. The major results obtained were as follows:

1. In general, specimens cut from blocks had lower average tensile strengths than CTS specimens over the temperature range investigated (550° to 870° C). Machined-from-block specimens of alloy R had greater average elongation than CTS bars. In alloy S, casting size had little effect on elongation.

2. Alloy R generally showed greater strength but lower elongation than alloy S.

3. Stress rupture strength at 760° C for the MFBK specimens was lower than the strength of CTS specimens by about 30 to 35 MPa for both alloys R and S. At 890° C the stress rupture strength of MFBK specimens of alloy R was lower than the strength of CTS specimens but little effect was noted for alloy S.

4. The stress rupture elongation was generally greater for alloy S than for alloy R but in both alloys the CTS specimens showed 2 to 3 percent greater elongation than MFBK specimens.

5. At the higher temperatures, the CTS specimens of both alloy R and alloy S had stress rupture strengths about 30 MPa less than previously reported data for machined-from-blade specimens.

6. The microstructure of MFBK specimens was significantly coarser than for the CTS specimens. The eutectic γ' nodules in blocks were about five times larger than in the CTS specimens, while the fine γ' was approximately twice as large. No significant differences were noted in the chemical composition of microconstituents between alloy R and S or between cast blocks and CTS specimens when measured by energy dispersive analyses of X-rays.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 30, 1976,
505-01.

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TABLE I. - CHEMICAL ANALYSES FOR TRW-NASA VIA MODIFICATIONS

Modification	C	Co	Zr	B	Cb	Cr	Hf	Ta	W	Al	Ti	Mo	Re	Ni
R:														
Aim	0.08	7.5	0.18	0.025	0.5	8	0.8	7	4	5.4	1	3	---	Balance
Actual	.075	7.2	.27	.035	.61	8.1	.81	7.0	3.8	6.0	.68	3.0	---	↓
S:														↓
Aim	.10	7.5	.13	.020	.5	8	.8	6	5.8	5.4	1	2	---	↓
Actual	.096	7.4	.12	.028	.49	8.3	.71	6.1	5.8	5.5	.71	2.0	---	↓
TRW-NASA VIA (nominal)	.13	7.5	.13	.02	.50	6.1	.43	9.0	5.8	5.4	1.0	2.0	0.5	↓

TABLE II. - TENSILE TEST RESULTS FOR TRW-NASA

VIA MODIFICATIONS R AND S

Casting	Test temperature, °C	Ultimate strength, MPa	2-Percent yield strength, MPa	Elongation, percent	Reduction in area, percent
Modification R					
CTS[a]	Room	974	858	5.9	6.4
		1037	863	3.3	8.5
CTS	550	854	800	1.3	3.5
		1109	809	7.9	9.3
Block		886	696	5.4	7.8
		868	716	5.0	9.3
CTS	650	928	812	2.3	4.3
		1116	811	7.9	9.3
Block		894	711	4.7	4.3
		905	714	6.1	11.1
CTS	750	914	855	1.4	2.7
		1066	898	5.3	8.1
Block		922	705	6.1	10.8
		958	745	5.7	7.7
CTS	870	744	567	1.3	2.8
		813	318	7.2	12.3
		792	279	3.2	5.9
Block		707	655	6.5	10.1
Block	860	734	687	6.2	10.2
CTS	1000	474	337	4.4	6.3
		484	342	8.9	12.3
Modification S					
CTS	Room	931	805	3.8	7.2
		977	789	5.1	7.8
CTS	550	1066	747	8.1	11.7
		964	709	5.3	7.7
Block		850	650	6.5	11.5
		798	647	6.2	10.4
CTS	650	1036	715	8.4	11.9
		1028	831	7.2	8.0
Block		811	647	5.4	8.1
		745	627	4.1	9.3
CTS	750	1011	741	7.7	10.1
		1000	732	4.9	6.6
Block		840	664	4.2	7.7
		875	656	6.1	7.7
CTS	870	762	589	9.9	15.3
		763	538	11.6	12.3
Block		737	627	8.5	13.5
Block	860	769	613	10.7	12.4
CTS	1000	412	289	5.5	7.8
		414	332	14.0	18.9

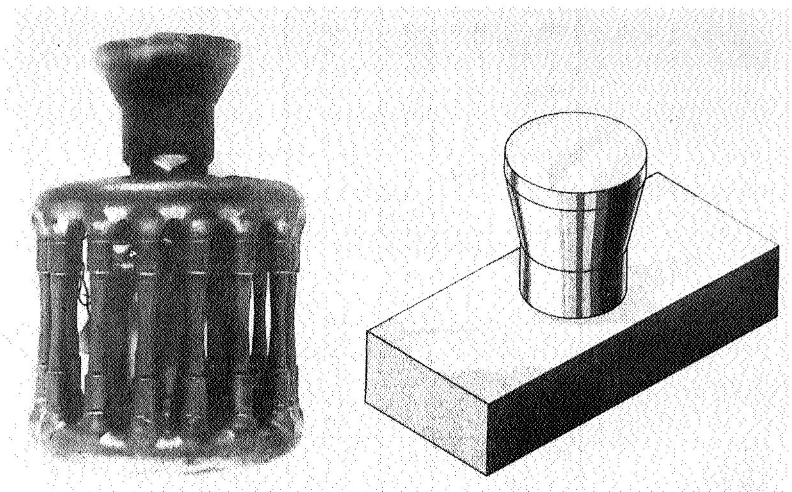
[a]Cast to size, CTS.

TABLE III. - STRESS RUPTURE TEST RESULTS

FOR TRW-NASA VIA MODIFICATIONS R AND S

Casting	Test condition, °C/MPa	Life, hr	Elongation, percent	Reduction in area, percent
Modification R				
CTS[a]	760/655	260.0	3.5	3.9
		287.7	5.3	10.8
Block		96.8	2.8	4.3
		67.5	2.7	6.6
		49.8	2.0	8.5
CTS	760/621	481.4	4.0	7.0
		707.4	7.0	9.3
		668.5	5.0	8.5
Block		187.7	4.0	6.6
		207.2	3.0	5.1
		209.1	3.1	3.5
CTS	890/414	3.7	1.6	2.0
		54.9	5.7	5.9
		60.3	6.8	8.5
CTS	890/276	402.0	2.5	3.5
		548.3	3.9	4.7
		496.3	3.8	4.3
Block		135.9	3.8	4.7
		149.1	4.5	4.7
CTS	1000/276	2.6	4.3	3.9
		5.8	4.8	6.3
		5.7	4.9	5.9
CTS	1000/172	32.7	2.5	1.6
		19.4	2.1	1.6
		37.5	3.2	2.4
CTS	1040/172	7.7	2.4	2.4
		7.7	3.5	3.1
		8.3	2.9	2.4
Modification S				
CTS	760/655	261.1	4.1	6.6
		66.1	6.2	7.0
		303.0	8.7	10.1
Block		193.2	4.1	11.1
		111.7	3.0	8.1
		85.8	2.9	3.1
CTS	760/621	501.5	5.4	8.5
		624.7	7.1	9.7
		275.1	3.6	7.0
Block		207.3	3.2	13.0
		140.9	3.1	10.0
		145.2	2.4	7.0
CTS	890/414	22.1	10.1	13.4
		23.4	12.0	14.1
		22.8	8.7	11.5
CTS	890/276	408.8	4.6	7.0
		345.2	5.8	10.1
Block		153.0	5.3	4.3
		287.3	6.1	9.0
CTS	1000/276	2.2	7.3	11.2
		2.9	9.0	10.4
		1.0	10.1	13.1
CTS	1000/172	33.7	4.3	4.7
		37.1	4.3	3.9
		36.9	3.9	3.9
CTS	1040/172	4.9	2.6	5.9
		6.1	3.5	3.9
		6.0	4.5	4.3

[a]Cast to size, CTS.



(a) Cast-to-size specimen cluster. (b) Block casting.

Figure 1. - Castings.

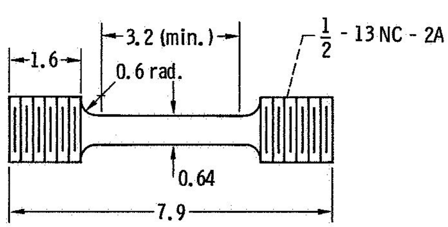


Figure 2. - Schematic of standard aircraft quality control specimen. (All dimensions in cm.)

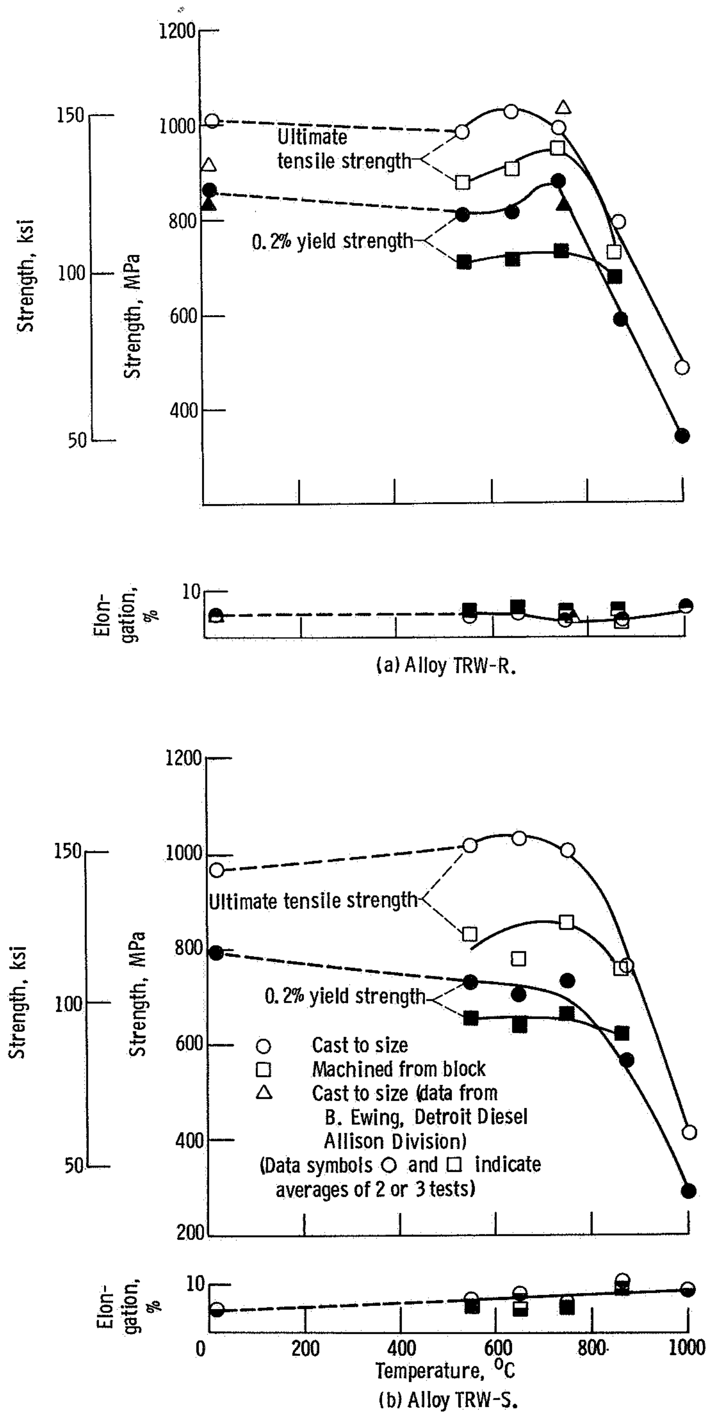


Figure 3. - Effect of temperature and casting geometry on tensile properties of alloys TRW-R and TRW-S.

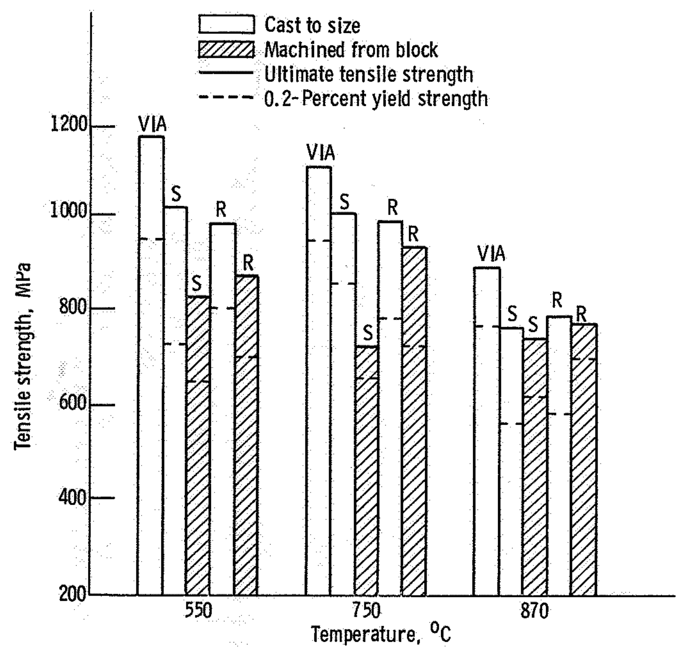


Figure 4. - Comparison of tensile properties of alloys. Alloy VIA data from reference 4.

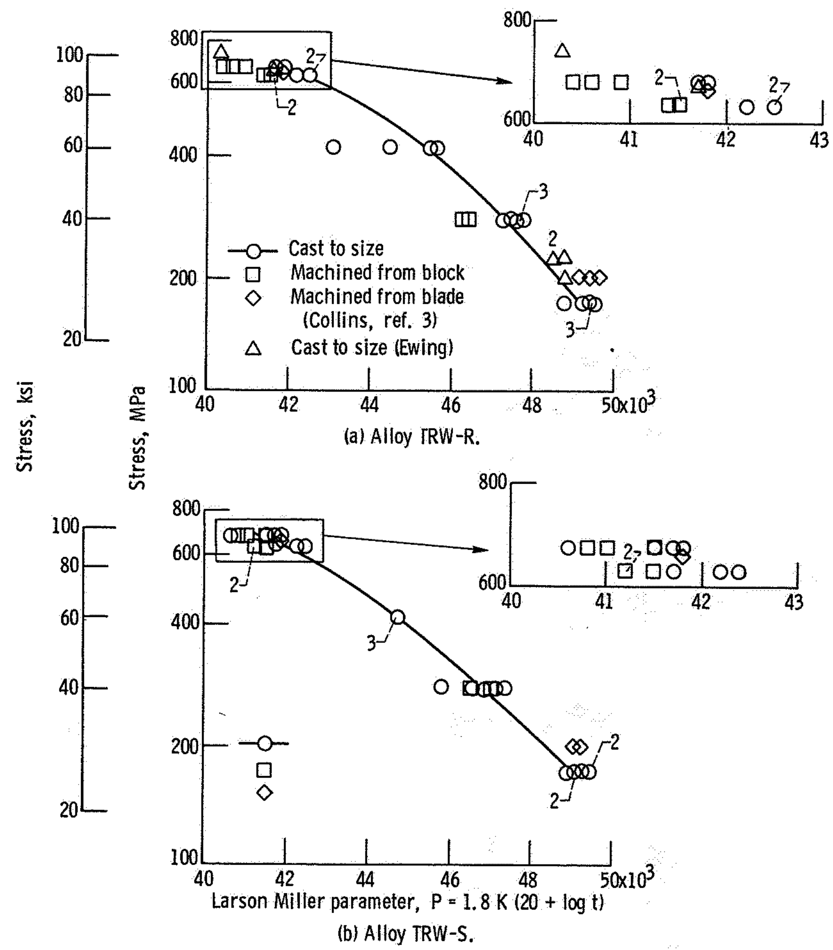


Figure 5. - Effect of casting geometry on stress rupture properties of alloys TRW-R and TRW-S.

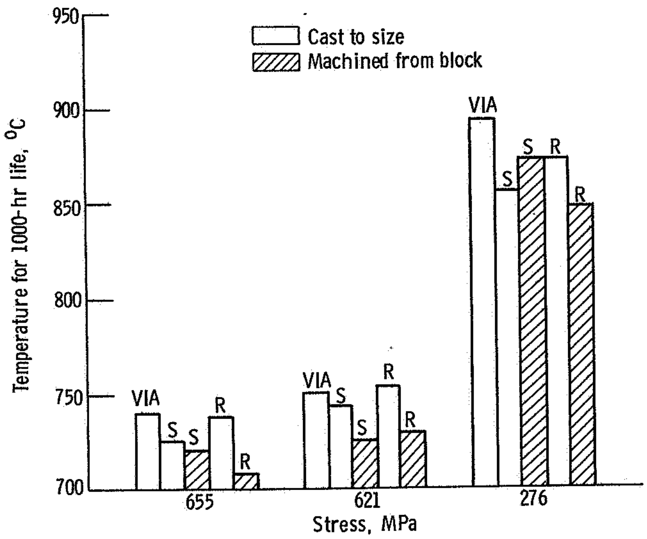
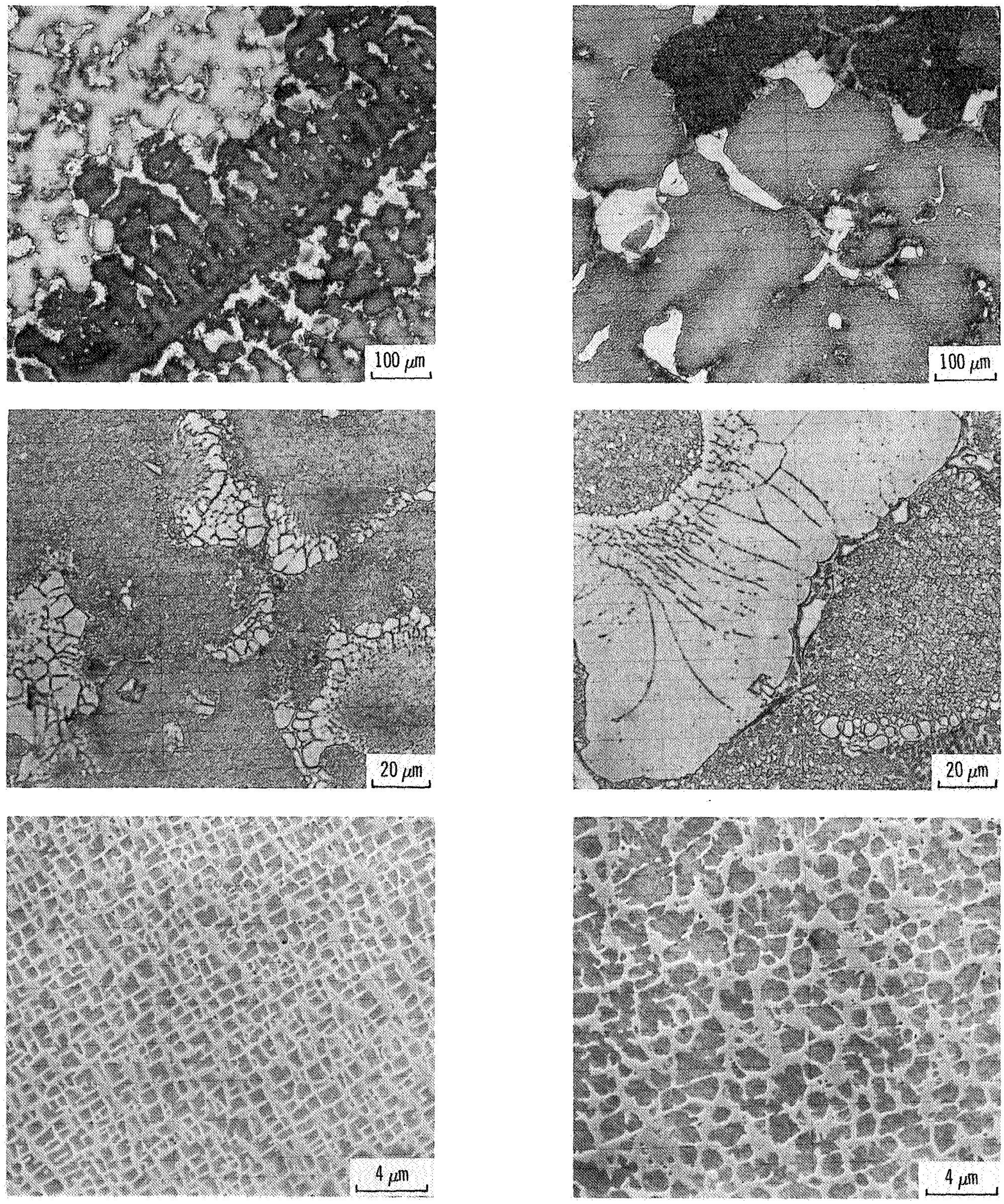


Figure 6. - Comparison of stress rupture properties of alloys. Alloy VIA data from reference 4.



(a) Cast-to-size specimens.

(b) Machined-from-block specimens.

Figure 7. - Microstructures of alloy TRW-R.

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