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Properties and Microstructures for Dual Alloy Combinations of Three Superalloys with Alloy 901

Fredric H. Harf
Lewis Research Center
Cleveland, Ohio

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PROPERTIES AND MICROSTRUCTURES FOR DUAL ALLOY COMBINATIONS

OF THREE SUPERALLOYS WITH ALLOY 901

Fredric H. Harf
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 4415

SUMMARY

A single component in a aircraft engine may operate in markedly different temperature and stress regimes. For example, the aircraft turbine disk may have a highly stressed hub operating below 500 °C, while its rim may see temperatures above 650 °C but at lower stress levels. The service lives of such components could be improved by forming the components from two (or more) alloys so as to obtain the most apporopriate local properties.

An approach to obtaining such parts is to hot isostatically press powders into the desired configuration and then to bring out the desired properties with a single heat treatment. In this study dual alloy specimens were fabricated and tested to provide further proof of the concept and processes involved. A high iron-nickel content superalloy was selected for the hub Alloy 901, and René 95, Astroloy, and MERL 76 were selected as possible rim superalloys. Powders of these alloys were hot isostatically pressed singly, in 50-50 mixtures with Alloy 901, or as a layer of a potential rim alloy in contact with Alloy 901. Each rim alloy was given the Alloy 901 heat treatment sequence or that recommended for it in disk use. Alloy 901 was given the four heat treatments. The materials were tested in tension between 350 and 750 °C and in stress rupture at 650 and 750 °C. Alloy 901 performed best with its own heat treatment and very well with that for MERL 76. For René 95 and Astroloy the Alloy 901 heat treatment gave superior results. MERL 76 displayed the best properties when its own heat treatment was applied. Alloy 901 was the weakest of the four alloys at all temperatures. It failed in all layered specimens and provided the crack propagation path in alloy mixtures.

Microstructural examination of the heat treated specimens showed that these combinations of alloys did not cause the formation of phases not present in the original alloys. Strengthening results from the precipitation of Ni_3Ti in Alloy 901 and of γ' (Ni_3Al) in the other alloys. When the alloys are mixed or in close contact, as where the alloys meet in the layered combinations, the formation of Ni_3Ti is suppressed by diffusion in the interface.

INTRODUCTION

Natural resources are unevenly distributed on the crust of the Earth; consequently, materials which are scarce or difficult to extract from the available deposits must be imported into the United States. Among the metals which fall into this category are the "strategic elements" cobalt, chromium, tantalum, and columbium (ref. 1). To reduce the consumption of these elements substitutes should be found for aerospace applications.

Aircraft gas-turbine disks are an example where potential savings can be obtained. When these disks operate at full power, they experience simultaneously a wide range of temperature and stress regimes. The rim is exposed to high temperatures, and the stresses acting on it induce plastic strain which eventually cause failure by creep rupture. On the other hand, the hub, removed from the stream of hot gases, remains at a lower temperature but must withstand high stresses.

Turbine disks, therefore, have been the subject of many studies aimed at expanding their operational capabilities, including the concept of dual properties. In the case of dual properties can be obtained by combining into a disk different alloys embodying the properties most appropriate for meeting the local criteria. The concept has the potential of conserving strategic or costly alloying elements (refs. 2 and 3) by the substitution of alloys containing domestically produced or cheaper elements. Approaches such as joining two alloys by diffusion bonding (ref. 4), by casting one against another which had been previously consolidated, or by powder metallurgy processes (refs. 5 to 7) have been considered.

Among the attractive features of the powder approach are close compositional control, fine grain size of the resultant material, and near-net shape components. Disks can be fabricated by hot isostatically pressing (HIP) prealloyed powders. In the case of dual alloy disks, there can be a prepressed rim into which loose powder for the hub is HIPed (ref. 7), or, if a way can be found to accurately locate where rim and bore powders meet, powders only may be used. When one of the alloys is prepressed, it must be thoroughly cleaned and positioned in such a way that, in the final HIP consolidation, it is exposed only to well-balanced, moderate stresses. Such a requirement was considered outside of the scope of the study; therefore, powders only were used.

Specimens composed of equal-weight mixtures of two alloy powders provided study of the interfaces between the alloys. To achieve the maximum conservation of strategic elements one of the superalloys selected for the combination had a high iron content.

The objectives of the program were to determine by mechanical testing and metallographic examination the compatibility of a high-iron-content, no-cobalt superalloy with nickel-based superalloys and to determine a suitable, common heat treatment to form components of these combinations. The mechanical property results of this study may guide the designer who wants to determine where the joint between two alloys should be located and how the design of the part should accommodate the properties strengths of the materials.

MATERIALS[1] AND PROCEDURES

Alloy Selection and Preparation

Chosen to represent typical rim alloys were René 95 and Astroloy, which both are currently used in disks produced by powder metallurgy, and the experimental alloy MERL 76 (ref. 8). Powders for these alloys had been used in previous research (ref. 9) and were readily available. The selection of the alloy for hub use was based on the conservation of strategic elements (refs. 2 and 3), strength, and grain growth characteristics of candidate alloys (ref. 10). The alloy to be chosen was to be preferably iron-base, contain none of the strategic elements (cobalt, tantalum, or columbium), maintain high strength at temperatures up to 650 °C, and retain a fine grain size while undergoing a heat treatment required to optimize the properties of the rim alloys in the combinations. No alloy containing over 50 wt % iron could meet these criteria. The most suitable alloy was the iron-nickel Alloy 901 (also referred to as Incoloy Alloy 901). The alloy is commonly used only in the wrought condition (ref. 9); thus the present work represents its first known tests in the hot isostatically pressed powder metallurgy (HIP-PM) form. All alloys were vacuum induction melted, cast, remelted, and argon atomized. Analyzed compositions and sieve analysis of the fractions used in this work are presented in table I.

Powder Processing

The cans for HIPing, made from AISI 304 stainless steel were approximately 100 mm long with a diameter of 18 mm and a wall thickness of 1.5 mm. Individual cans were filled either with powders from each composition or with powders in which equal portions by weight of Alloy 901 had been mixed with René 95, Astroloy, or MERL 76, or with layered combinations wherein cans were half filled with Alloy 901 and then filled to the top with one of the other alloys. The filled cans were held overnight in a vacuum at 350 °C, after which the filler necks were sealed by electron beam welding. The sealed cans were hot isostatically pressed at 1100 °C for 2 hr at a pressure of 135 MPa.

Heat Treatment

To determine the response of dual alloy combinations, heat treatments commonly used for both of the component alloys were given to each alloy mix, layered specimen, and the component alloys. Thus, HIPed cans containing Alloy 901 were given its own heat treatment sequence and the sequences of René 95, Astroloy, and MERL 76 powder. Each of the other three alloys was given its own and the Alloy 901 heat-treatment sequence. The heat treatment sequences used are shown in table II. The atmosphere used for all heat treatments was air. In addition to these heat treatments, some material of every type was overaged at 650 °C for 1500 hr.

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[1]René 95 in a trademark of General Electric Company. Astroloy is a trademark of Teledyne-Allvac. Incoloy Alloy 901 is a trademark of the International Nickel Co., Ltd. MERL 76 is produced by United Technologies Corporation.

Mechanical Tests

Heat-treated blanks were machined into test specimens used for tensile and stress rupture tests (fig. 1). Tensile tests on individual alloys, mixed alloys, and layered alloys in the heat treated conditions were run at 350, 500, 650, and, except for layered alloys, 750 °C and, after overaging, at 500 and 650 °C. Stress-rupture tests were performed on materials in all conditions at 650 °C and on as-heat-treated alloys and mixtures at 750 °C. Test procedures conformed to applicable ASTM recommended practices.

Metallography

Specimens for metallographic examination were first ground through 600-grit silicon carbide papers and then polished on cloth covered wheels with diamond paste or alumina slurries to 0.5 μm fineness. Marble's reagent was generally used for etching, but for scanning-electron-microscopy preparation a solution of 33 percent hydrochloric acid, 33 percent acetic acid, 33 percent water, and 1 percent hydrofluoric acid was used.

RESULTS

Mechanical Tests

Tensile test results for individual alloys are shown in tables III to VI, for mixed alloys in tables VII to IX, and for layered alloy combinations in tables X to XII. Stress-rupture test results are presented on tables XIII to XVI.

Comparison of the test results for Alloy 901 (tables III, XIII, and XIV) shown in figures 2 and 3 reveals that below 500 °C the heat treatment normally specified for the alloy provided a better combination of tensile and creep-rupture properties than those specified for the other alloys used in this program. The advantage of this heat treatment persisted even after 1500 hr overaging at 650 °C. The next best heat-treatment for Alloy 901 was the one specified for MERL 76, which provided the greatest tensile strength at 650 and 750 °C; but a thread failure in stress-rupture testing at 650 °C (table XIII) revealed potential notch brittleness.

Tensile and rupture strengths of René 95 (tables IV, XIII, and XIV figs. 4 and 5) show that when the alloy was given the heat Alloy 901 heat treatment sequence, its properties appeared to be better than when given its standard heat treatment. In general, higher strengths and ductilities were observed. Thread failures in stress rupture were obtained at 650 °C with the René 95 heat treatment (table XIII) and at 750 °C with the Alloy 901 heat treatment (table XIV). Overaging tended to lessen the differences between the two heat treatments.

The tensile and rupture strengths for Astroloy, (tables V and XIII) are summarized in figures 5 and 6. This alloy displayed greatly improved properties when given the Alloy 901 heat treatment compared with its standard disk type heat treatment both in the as-heat-treated and overaged conditions.

On the other hand MERL 76, while gaining in tensile strength, suffered a loss of ductility and in rupture strength when given the Alloy 901 heat treatment sequence instead of its own (tables VI, XIII, and XIV; figs. 5 and 7). Overaging at 650 °C did not remove this deficiency.

Mixed alloys were meant to represent the interface between the nickel-base superalloys and Alloy 901. The strength of these mixtures in tensile as well as stress-rupture tests always was intermediate between that of Alloy 901 and the other alloy present. Thus, while for rupture tests at 650 °C René 95, Astroloy, and MERL 76 withstood a stress of 900 MPa and Alloy 901 of 500 MPa for a reasonable length of life, it was thought more prudent to load the mixtures to 700 MPa. For rupture tests at 750 °C the stress was set at 400 MPa; it had been 475 for the high-strength alloys and 325 MPa for Alloy 901.

The mixtures of René 95 and Alloy 901 displayed higher tensile strength in the as-heat-treated and overaged conditions with the Alloy 901 heat treatment than with the René 95 heat treatment (table VII; fig. 8). Elongations were very low in tensile tests at 750 °C and in all stress-rupture tests (table XV). No consistent trend was evident in the stress-rupture results (table XV; fig. 9) with heat treatment.

The mixtures of Astroloy and Alloy 901 showed better tensile strengths (table VIII; fig. 10) and rupture strengths (table XV; fig. 9) when the mixtures were heat treated like Alloy 901. This heat treatment, however, resulted in low elongation in 750 °C tensile tests and in 650 and 750 °C stress-rupture tests. Overaging appeared to enhance the tensile strength but reduced the stress-rupture lives for both heat treatments.

There was no significant difference in tensile strengths for the two heat treatments given to the mixture of MERL 76 and Alloy 901 (table IX; fig. 11). Ductility was improved with the Alloy 901 heat treatment. However, the stress-rupture strengths of specimens given the MERL 76 heat treatment were higher and rupture lives were markedly longer, while ductilities were not greatly different (table XV; fig. 9). Overaging reduced the ductilities, increased the tensile strength, and reduced rupture lives to a minor degree.

Layered combinations all failed in the lower strength Alloy 901. Tensile strengths for all combinations were therefore equal to those of Alloy 901 (compare tables X, XI, and XII with table III). Stress-rupture tests were run at 650 °C and 500 MPa, and, again, the lives of layered specimens equaled those of Alloy 901 (compare table XVI with table XIII). Ductilities were also those of the weaker alloy.

Overaging effects were similar to those observed for Alloy 901. However, in the overaged combinations with René 95 the failures, while originating in Alloy 901 also partially involved the joints (fig. 12.)

Microstructures

The Alloy 901 microstructures of figures 13 to 15 show that prior particle boundaries are very much in evidence. These boundaries were not eliminated by any of the four heat treatments given the alloy. The principal difference in the as-heat-treated microstructures (fig. 13) was the quantity of the fine Ni_3Ti particles scattered throughout the matrix. A greater quantity of

Ni_3Ti particles was present after the René 95 heat treatment (fig. 13(b)) and the least after the MERL 76 heat treatment (fig. 13(d)). There appeared to be an inverse relationship between the quantity of Ni_3Ti particles and the final heat treating temperatures (table II). The final heat-treatment temperatures were for Astroloy and MERL 76, 760 °C (figs. 13(c) and (d)); for Alloy 901, 720 °C (fig. 13(a)); and for René 95, 650 °C. That 650 °C had a potent effect on Ni_3Ti content can be seen in by comparing figures 13 and 14. The higher magnification photomicrograph of overaged Alloy 901 with its standard heat treatment reveals fine Ni_3Ti particles scattered throughout the grains and decorating the grain boundaries (fig. 15).

When René 95 was given the Alloy 901 heat treatment, it displayed a more finely distributed Ni_3Al γ' precipitate (fig. 16(b)) than when its standard heat treatment is used (fig. 16(a)). This difference even prevailed after overaging at 650 °C (figs. 16(c) and (d)). The finer precipitate in René given the Alloy 901 heat treatment sequence is attributed to the lower intermediate aging temperature, which for the Alloy 901 sequence was 790 °C and for the René 95, sequence was 870 °C.

Again, in Astroloy, coarsening of Ni_3Al γ' particles was more pronounced with the Astroloy heat treatment (fig. 17(a)) than after the Alloy 901 heat treatment (fig. 17(b)). This difference did not disappear after overaging at 650 °C (figs. 17(c) and (d)).

The microstructures of as-heat-treated and overaged MERL 76 are represented in figure 18. The higher partial solutioning temperature (1175 °C) which forms part of the heat treatment for MERL 76 caused the residual Ni_3AL γ' to agglomerate into discrete particles at the triple points of the grain boundaries (fig. 18(a)). Similar structures were observed after a five step heat treatment with a maximum temperature of 1163 °C (ref. 11). Such particles did not form when the alloy was subjected to the lower partial solutioning temperature of 1100 °C, standard for Alloy 901 (fig. 18(b)), but the higher aging temperature for this alloy caused the precipitation of more and coarser γ' particles throughout the grains. Overaging did not reduce the coarseness of the fine γ' particles (fig. 18(c) and (d)).

Mixing of the alloys produced a microstructure in which larger individual grains of the two alloys separated by diffusion zones can be distinguished. Representative structures of such mixtures are shown in figure 19. Overaging shrinks the islands of undiffused alloy (fig. 20). Dependent on time and temperature, diffusion eventually should produce a structure of uniform composition.

Joints between Alloy 901 and René 95, Astroloy and MERL 76 are shown in figure 12(b), 21(a), and 21(b). In all cases an intimate bond exists, and a thin diffusion zone has formed between the two alloys. This diffusion zone widens with overaging, as can be seen by comparing figures 21(a) and (b). In general, the diffusion zone does not represent a line of weakness, but in some cases where a stress-rupture failure originated near the joint, a portion of the crack may actually have followed it (table XVI and fig. 12).

DISCUSSION

In analyzing these results one fact must be kept in its proper perspective: in dual alloy combinations the joint occupies only a very small portion of the part, and like a weld, it should be placed in a noncritical location. It is important that the alloys be compatible enough to permit bonding without weakening of the joint area. If this is achieved, then its properties, as represented by the mixed alloys, are not of paramount importance. From this study it can be concluded that Alloy 901 forms strong bonds with René 95, Astroloy, and MERL 76, because the properties of the joint, that is, mixed alloys, are intermediate to those of the alloys present. This was assumed and confirmed, therefore, it should be easy to accommodate these properties in the design of a dual alloy part. Furthermore, the microstructures of mixtures and joints indicate that the joints and their diffusion zones are free of new and detrimental phases.

More important are the actual properties of the alloys represented in a dual alloy part. To avoid unpredictable microstructures, which might occur at interfaces if each alloy component were given a different heat treatment, a uniform heat treatment for an entire part is highly desirable. For this purpose the materials were given heat treatments applicable to one or the other alloy in a combination. Alloy 901, at temperatures above 500 °C, where, admittedly, it loses much of its lower temperature strength, showed improved properties when given the MERL 76 heat treatment. It is worth noting that the standard heat treatments for René 95 and Astroloy have intermediate aging steps at 870 and 970 °C. At these temperatures, large portions of the partially solutioned Ni_3Ti in Alloy 901 can be precipitated as fine particles. This accounts for the greater amount of Ni_3Ti particles observed at low magnifications (figs. 13 and 14) with heat treatments for René 95, and Astroloy compared with heat treatments for Alloy 901 and MERL 76. When Alloy 901 is heat treated by the former two procedures, there may be little Ni_3Ti left in solution, which can, by aging at 720 and 760 °C, precipitate at lower temperatures as ultrafine particles to provide the higher strength (ref. 12). Indeed, the higher tensile strength obtained by overaging appears to confirm this point, especially for the MERL 76 heat treatment (table III). Based on overall tensile and stress-rupture test results, the heat treatments for Alloy 901 should be in order of preference, MERL 76, Alloy 901, René 95, and Astroloy. A certain loss of ductility was observed with the MERL 76 heat treatment (table XIII), but it appears that this can be alleviated by an additional aging treatment at 650 °C, as is evidenced by the improved elongations and reductions of area after overaging.

Tensile and creep-rupture strengths of René 95 showed only slight improvements with the Alloy 901 heat treatment (figs. 4 and 5), and microstructurally no great difference can be observed between the two heat treatments (fig. 16). However, for Astroloy, despite the similarity of microstructures (fig. 17), the Alloy 901 heat treatment provides much better properties than the standard Astroloy heat treatment (figs. 5 and 6). MERL 76 shows major differences in the microstructure (fig. 18). Its standard partial solutioning temperature is 1175 °C, which results in substantial solutioning of fine γ' particles and causes agglomeration of the remaining partially solutioned γ' (figs. 18(a) and (c)). The maximum heat-treating temperature of 1100 °C given Alloy 901 seems to act more like a high-temperature aging treatment on MERL 76. Coarse γ' particles are evident throughout the structure (figs. 18(b) and (d)) and probably not much γ' remains in the γ matrix to precipitate as fine particles at the lower aging temperature of 790 °C. Thus, the properties of MERL 76 given the Alloy 901 heat treatment are substantially poorer than those for the alloy with its standard heat treatment.

The results of overaging were somewhat mixed. In tensile tests the ultimate and yield strengths were enhanced, generally at the expense of ductility. This was probably caused by the formation of additional ultrafine γ' particles. However, when the overaged material was tested in stress rupture at 650 °C, the rupture life decreased, while the ductility of single alloys increased. Here, the more numerous ultrafine γ' particles, stressed over the longer time, were less stable than the coarser particles resulting from the normal heat treatment. Overaging decorated the grain and previous particle boundaries of Alloy 901 with Ni_3Ti. But near the interfaces with Ni_3Al (γ') forming alloys, diffusion appeared to be rapid enough to reduce the concentration of titanium so that the precipitate was not observed. (Compare figs. 17 and 20(b).) On the whole, the alloys and their combinations underwent little change from overaging. This is a good indication of alloy stability, and augurs well for the use of the alloy combinations tested in this program.

SUMMARY OF RESULTS

Dual alloy combinations were produced by hot isostatically pressing prealloyed powders of Alloy 901 with René 95, Astroloy, and MERL 76 as distinct joined layers. The combinations were given a single heat treatment appropriate for each of the constituent alloys. The effects of these heat treatments on mechanical properties and microstructures were determined on each alloy separately and each two alloy combination as mixed powders.

It was shown that

1. The combinations of Alloy 901 with René 95, Astroloy, and MERL 76 can produce sound metallurgical bonds of greater strength than that of the weaker constituent alloy and free of phases not present in either constituent.

2. Over the range from 300 to 750 °C,

a. Alloy 901 shows good strength and ductility when given its standard heat treatment or that of MERL 76. The René 95 or Astroloy heat treatments result in reduced tensile and stress-rupture strength.

b. René 95 and Astroloy are stronger with the Alloy 901 heat treatment than with that considered standard for their composition.

c. the MERL 76 heat treatment is better than the Alloy 901 heat treatment for the MERL 76 alloy.

3. In two-layered alloy combinations failures always originated in Alloy 901.

CONCLUDING REMARKS

This research shows how two superalloys, disparate in composition can be joined by the HIP-PM process and form a strong, integral bond. The implications are, and these have been demonstrated in other work (refs. 4 to 7), that dual alloy combinations between various nickel-base (and iron-nickel-base) superalloys are a possible means of enhancing the local properties of gas-turbine-engine components and of conserving costly strategic materials.

The results also suggest that the heat treatments now considered standard are not necessarily the only and best heat treatments that could be given a material. Rather, heat treatment should be tailored to the application. Often such tailoring must be based on a somewhat wider range of properties than those of tensile and stress-rupture strength.

Finally, HIP-PM for dual alloys has its limitations, as was pointed out by Kortovich and Marder (ref. 7). Some of the major problems are gravity-induced settling and the inability to accurately locate interfaces for critical applications. Further development along these lines is necessary before the promising results obtained herein can be carried into actual hardware.

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TABLE I. - ALLOY DATA

(a) Analyzed composition

Element content	Alloy 901	René 95	Astroloy	MERL 76
	Composition, wt %			
Ni	43.66	[a]61.43	[a]55.21	[a]55.48
Fe	[a]35.90	0.33	0.12	0.14
Cr	11.91	13.49	14.99	11.95
Mo	5.77	3.42	5.00	3.04
Co	.055	7.90	17.09	18.11
W	-------	3.38	------	------
Hf	-------	------	------	.43
Cb	-------	3.70	------	1.45
Al	.038	3.65	4.05	5.13
Ti	2.58	2.57	3.45	4.16
Zr	-------	.058	.01	.06
C	.068	.059	.047	.028
B	.019	.009	.028	.018

(b) Sieve analyses

Mesh	Alloy 901	René 95	Astroloy	MERL 76
	Powder fractions, %			
-80 + 100	0	7.7	10.7	12.7
-100 + 140	1.0	13.1	17.0	22.7
-140 + 200	17.0	16.7	17.7	20.8
-200 + 325	33.0	25.4	26.1	21.3
-325	49.0	37.1	28.5	22.5

[a]Calculated based on analyzed composition of other elements in alloy.

TABLE II. - HEAT TREATMENT SEQUENCES USED FOR INDIVIDUAL AND COMBINED ALLOYS

Specified for alloy	Temperature, °C	Time, hr	Quench[a]
Alloy 901	1100	2	WQ
	790	2	AC
	720	24	AC
René 95	1120	1	RAC
	870	1	AC
	650	16	AC
Astroloy	1100	4	WQ
	870	8	AC
	980	4	AC
	650	24	AC
	760	8	AC
MERL 76	1175	2	AC
	760	8	AC
Overaging	650	1500	AC

[a]AC - air cool; RAC - rapid air cool; WQ - water quench.

TABLE III. - TENSILE TEST RESULTS FOR ALLOY 901

Heat treat sequence[a]	Test temperature, °C	Ultimate tensile strength, MPa	Yield strength, MPa	Elongation, %	Reduction in area, %
After heat treatment					
Alloy 901	350	1190	900	11.7	27
	500	1150	867	14.4	24.3
	650	861	759	6.5	14.1
	650	835	731	3.4	13.8
	750	656	633	2.2	7.8
René 95	350	1290	720	16.4	32.8
	350	1060	707	25.9	39.5
	500	1020	700	8.8	2.3
	650	833	651	10.4	13.9
	650	817	631	2.3	13.4
	750	595	560	4.9	10.7
Astroloy	350	1100	800	11.0	22.5
	500	1090	790	13.5	31.0
	650	856	746	6.8	11.2
	650	897	778	5.2	11.0
	750	625	606	3.2	2.0
MERL 76	350	1140	840	8.8	35.2
	500	1110	810	17.0	31.9
	650	950	794	3.6	7.4
	750	689	674	3.0	5.9
After overaging					
Alloy 901	500	1173	913	5.7	10.6
	650	893	776	6.8	14.0
René 95	500	1030	734	11.2	22.5
	650	804	643	15.3	16.2
Astroloy	500	1099	876	11.0	24.2
	650	873	769	11.3	11.2
MERL 76	500	1146	898	11.8	19.4
	650	911	809	7.4	12.6

[a]See Table II.

TABLE IV. - TENSILE TEST RESULTS FOR RENÉ 95

Heat treat sequence	Test temper-ature, °C	Ultimate strength, MPa	Yield strength, MPa	Elongation, %	Reduction in area, %
As heat treated					
René 95	350	1460	1270	5.3	7.3
	500	1460	1240	19.5	34.2
	500	1369	1245	1.7	8.7
	650	1457	1226	3.3	8.7
	650	1465	1256	5.7	12.4
	750	1130	1079	.4	5.9
Alloy 901	350	1530	1340	4.8	7.3
	500	1510	1310	7.6	12.0
	650	1404	1298	5.7	8.0
	650	1451	1259	4.0	5.9
	750	1269	1212	3.6	5.4
After overaging					
René 95	500	1570	1310	3.4	8.3
	650	1451	1219	3.4	8.3
Alloy 901	500	1554	1365	10.4	8.7
	650	1492	1246	3.0	12.5

TABLE V. - TENSILE TEST RESULTS FOR ASTROLOY

Heat treat sequence	Test temperature, °C	Ultimate strength, MPa	Yield strength, MPa	Elongation, %	Reduction in area, %
As heat treated					
Astroloy	350	1320	1030	11.0	17.2
	500	1410	1030	8.3	19.8
	650	1253	1047	5.1	11.0
	650	1251	1036	0.9	9.3
	750	1014	988	5.0	4.4
Alloy 901	350	1507	1175	8.9	14.9
	500	1440	1150	5.6	5.3
	650	1340	1134	8.8	11.9
	650	1257	1098	7.8	8.3
	750	1115	1065	7.1	9.7
After overaging					
Astroloy	500	1275	1108	4.0	8.7
	650	1310	1053	12.1	11.6
Alloy 901	500	1446	1194	7.3	13.6
	650	1397	1147	8.2	11.6

TABLE VI. - TENSILE TEST RESULTS FOR MERL 76

Heat treat sequence	Test temperature, °C	Ultimate strength, MPa	Yield strength, MPa	Elongation, %	Reduction in area, %
As heat treated					
MERL 76	350	1380	1090	9.9	12.0
	500	1270	1100	1.1	9.7
	650	1391	1082	23.3	12.6
	750	1109	1048	5.3	13.0
Alloy 901	350	1480	1170	6.5	16.2
	500	1360	1170	3.3	9.7
	650	1376	1157	8.4	11.6
	750	1130	1086	5.1	7.3
After overaging					
MERL 76	500	1533	1168	14.3	15.8
	650	1384	1115	23.8	22.5
Alloy 901	500	1441	1201	13.0	6.6
	650	1405	1175	10.2	13.6

TABLE VII. - TENSILE TEST RESULTS FOR MIXED RENE 95 AND ALLOY 901

Heat treat sequence	Test temper-ature, °C	Ultimate strength, MPa	Yield strength, MPa	Elongation, %	Reduction in area, %
As heat treated					
René 95	350	1387	1014	15.4	17.2
	500	1338	996	10.2	14.4
	650	1223	963	10.6	10.2
	650	1238	1009	5.0	7.1
	750	856	821	0.4	6.8
Alloy 901	350	1428	1064	15.0	14.4
	500	1422	1039	17.2	17.6
	650	1228	1034	6.0	5.1
	650	1211	1056	3.5	6.3
	750	935	884	0.9	7.8
After overaging					
René 95	500	1444	1064	11.3	13.5
	650	1172	1005	3.8	7.8
Alloy 901	500	1400	1132	5.8	10.7
	650	1253	1091	3.7	7.8

TABLE VIII. - TENSILE TEST RESULTS FOR MIXED ASTROLOY AND ALLOY 901

Heat treat sequence	Test temperature, °C	Ultimate strength, MPa	Yield strength, MPa	Elongation, %	Reduction in area, %
As heat treated					
Astroloy	350	1330	954	22.5	25.9
	500	1317	930	18.7	16.2
	650	1128	913	6.6	5.9
	650	1161	906	5.3	10.0
	750	839	806	1.8	4.9
Alloy 901	350	1385	1036	23.2	27.8
	500	1365	1016	19.1	20.8
	650	1229	1025	6.8	7.9
	650	1157	995	4.2	9.0
	750	902	871	0.6	6.8
After overaging					
Astroloy	500	1405	1023	13.5	12.2
	650	1150	966	8.9	10.7
Alloy 901	500	1391	1075	11.3	15.4
	650	1190	1034	6.7	9.7

TABLE IX. - TENSILE TEST RESULTS FOR MIXED MERL 76 AND ALLOY 901

Heat treat sequence	Test temperature, °C	Ultimate strength, MPa	Yield strength, MPa	Elongation, %	Reduction in area, %
As heat treated					
MERL 76	350	1427	1084	11.3	12.6
	500	1455	1069	13.4	16.3
	650	1275	1069	5.6	6.8
	750	963	948	1.0	4.0
Alloy 901	350	1462	1097	15.7	7.8
	500	1453	1091	17.4	17.1
	650	1233	1062	5.8	6.8
	750	971	939	5.9	2.4
After overaging					
MERL 76	500	1419	1138	6.5	11.1
	650	1251	1119	1.4	7.8
Alloy 901	500	1485	1153	11.8	13.0
	650	1273	----	5.0	9.8

TABLE X. - TENSILE TEST RESULTS[a] FOR LAYERED RENÉ 95 AND ALLOY 901 COMBINATIONS

Heat treat sequence	Test temperature, °C	Ultimate strength, MPa	Yield strength, MPa	Elongation, %	Reduction in area, %
As heat treated					
René 95	350	1106	770	11.0	17.2
	500	1075	740	20.6	30.3
	650	868	659	9.2	11.3
	650	866	679	2.6	13.3
Alloy 901	350	1209	935	10.3	34.2
	500	1155	860	14.3	28.7
	650	918	795	10.3	19.4
	650	915	820	7.6	18.2
After overaging					
Alloy 901	500	1184	915	10.8	20.2

[a]All failures occurred in Alloy 901.

TABLE XI. - TENSILE TEST RESULTS[a] FOR LAYERED ASTROLOY AND ALLOY 901 COMBINATIONS

Heat treat sequence	Test temperature, °C	Ultimate strength, MPa	Yield strength, MPa	Elongation, %	Reduction in area, %
As heat treated					
Astroloy	350	1127	783	15.1	32.4
	500	1119	834	10.4	32.8
	650	946	816	3.5	12.6
Alloy 901	350	1183	913	11.8	36.0
	500	1136	860	10.1	34.4
	650	963	876	3.1	11.0
After overaging					
Astroloy	500	1199	931	10.3	22.3
Alloy 901	500	1185	932	5.8	13.5

[a]All failures occurred in Alloy 901.

TABLE XII. - TENSILE TEST RESULTS[a] FOR LAYERED MERL 76 AND ALLOY 901 COMBINATIONS

Heat treat sequence	Test temperature, °C	Ultimate strength, MPa	Yield strength, MPa	Elongation, %	Reduction in area, %
As heat treated					
MERL 76	350	1040	731	9.1	36.8
	500	1037	690	14.5	34.9
	650	823	696	8.4	18.1
Alloy 901	350	1182	907	11.6	29.1
	500	1141	856	12.6	32.8
	650	907	798	2.4	9.3
After overaging					
MERL 76	500	1114	823	7.5	17.1
Alloy 901	500	1185	941	11.0	29.0

[a]All failures occurred in Alloy 901.

TABLE XIII. - RESULTS OF STRESS-RUPTURE TESTS OF ALLOYS AT 650 °C

Alloy	Heat treat sequence	Specimen condition	Stress, MPa	Time to failure, hr	Elongation, %	Reduction of area, %
Alloy 901	Alloy 901	As heat treated	500	23.6	5.5	5.0
		Overaged	500	42.7	3.6	6.8
	René 95	As heat treated	500	28.4	4.0	5.0
		Overaged	500	15.4	6.2	14.9
	Astroloy	As heat treated	500	8.4	[a]---	----
			500	21.6	3.5	4.8
		Overaged	500	40.1	3.2	7.4
	MERL 76	As heat treated	500	2.8	[a]---	----
			500	103.6	1.2	2.5
		Overaged	500	61.7	3.2	4.9
René 95	René 95	As heat treated	900	70.4	[a]---	----
			900	115	0.7	4.0
		Overaged	900	94.1	3.6	3.9
	Alloy 901	As heat treated	900	119	3.4	3.9
		Overaged	900	63.4	4.5	3.5
Astroloy	Astroloy	As heat treated	900	133	2.8	4.9
		Overaged	900	94.6	1.4	5.9
	Alloy 901	As heat treated	900	564	0.5	7.8
		Overaged	900	403	1.4	6.8
MERL 76	MERL 76	As heat treated	900	382	13.2	10.6
		Overaged	900	243	3.9	6.9
	Alloy 901	As heat treated	900	328	5.9	4.6
		Overaged	900	129	8.3	3.9

[a]Thread failure.

TABLE XIV. - RESULTS OF STRESS-RUPTURE TESTS OF ALLOYS AT 750 °C

Alloy	Heat treat sequence	Stress, MPa	Time to failure, hr	Elongation, %	Reduction in area, %
901	Alloy 901	400	0.9	2.3	4.0
		325	4.5	4.9	4.0
	René 95	325	3.6	4.6	5.9
	Astroloy	325	3.1	3.5	1.1
	MERL 76	325	8.6	1.2	2.5
René 95	René 95	475	15.6	2.9	3.0
	Alloy 901	475	17.5	3.5	2.0
		475	1.4	a	
Astroloy	Astroloy	475	28.6	4.0	3.9
	Alloy 901	475	45.8	2.2	4.9
MERL 76	MERL 76	475	106	4.0	5.4
	Alloy 901	475	30.0	2.7	2.0

[a]Thread failure.

TABLE XV. - RESULTS OF STRESS-RUPTURE TESTS OF MIXED ALLOYS

Combination of Alloy 901 with -	Heat treat sequence	Specimen condition	Time to failure, hr	Elongation, %	Reduction in area, %
Tests at 650 °C, and 700 MPa					
René 95	René 95	As heat treated	28.3	0.0	3.0
		Overaged	19.8	1.0	4.0
	Alloy 901	As heat treated	26.3	a	
		Overaged	82	0.0	3.0
Astroloy	Astroloy	As heat treated	29	1.0	4.0
		Overaged	23.4	4.0	0.2
	Alloy 901	As heat treated	74	a	
		Overaged	39.9	0.4	4.9
MERL 76	MERL 76	As heat treated	389	4.8	3.0
		Overaged	308	0.0	1.0
	Alloy 901	As heat treated	159	0.6	5.9
		Overaged	131	0.0	1.0
Tests at 750 °C, and 500 MPa					
René 95	René 95	As heat treated	6.0	1.0	1.0
	Alloy 901	As heat treated	12.4	0.7	1.0
Astroloy	Astroloy	As heat treated	8.8	1.2	2.0
	Alloy 901	As heat treated	12.8	0.0	2.0
MERL 76	MERL 76	As heat treated	45	1.2	2.0
	Alloy 901	As heat treated	25	2.0	2.0

[a]Thread failure.

TABLE XVI. - RESULTS OF STRESS RUPTURE TESTS OF LAYERED ALLOY COMBINATIONS

[Tests at 650 °C and 500 MPa.]

Alloy 901 layered with	Heat treat sequence	Specimen condition	Time to failure,	Elongation, %	Reduction in area, %	Failure in alloy
René 95	René 95	As heat treated	41.1	0.3	4.0	Alloy 901
		Overaged	21.9	6.5	7.8	[a]Alloy 901
	Alloy 901	As heat treated	43.5	1.3	4.9	Alloy 901
		Overaged	71.6	2.1	5.9	[a]Alloy 901
Astroloy	Astroloy	As heat treated	21.2	4.0	0.6	Alloy 901
		Overaged	59.5	2.4	5.9	Alloy 901
	Alloy 901	As heat treated	46.0	.8	4.9	Alloy 901
		Overaged	38.9	4.8	6.9	Alloy 901
MERL 76	MERL 76	As heat treated	19.1	0.8	4.8	Alloy 901
		Overaged	36.6	4.5	7.8	[a]Alloy 901
	Alloy 901	As heat treated[b]	20.9	---	---	---------
		Overaged[b]	21.9	---	---	---------

[a]Failure originated in Alloy 901 and extended into joint.
[b]Thread failure.

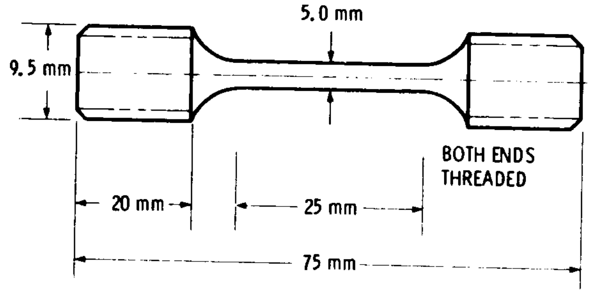

Figure 1. - Test specimen.

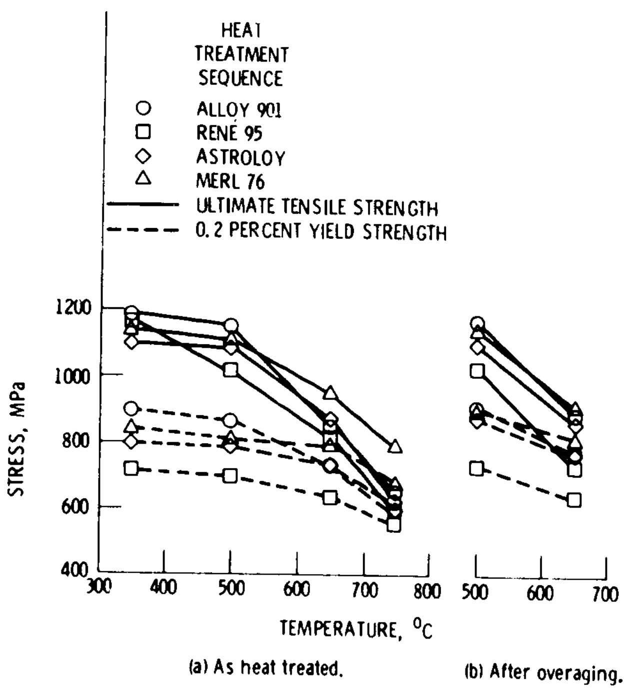

Figure 2. - Tensile properties of Alloy 901.

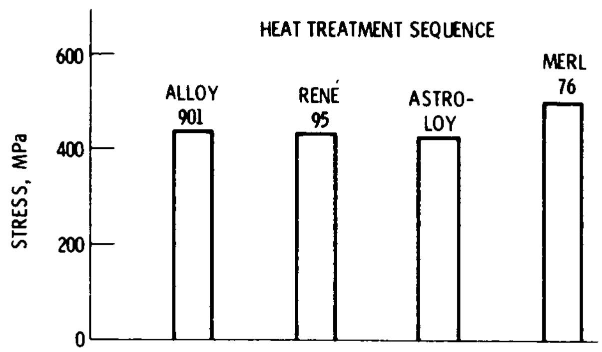

Figure 3. - Stress to rupture Alloy 901 in 100 hr at 650 °C.

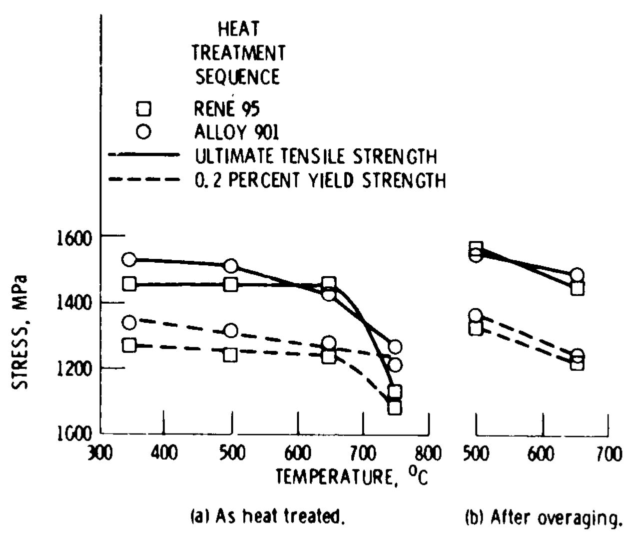

Figure 4. - Tensile properties of René 95.

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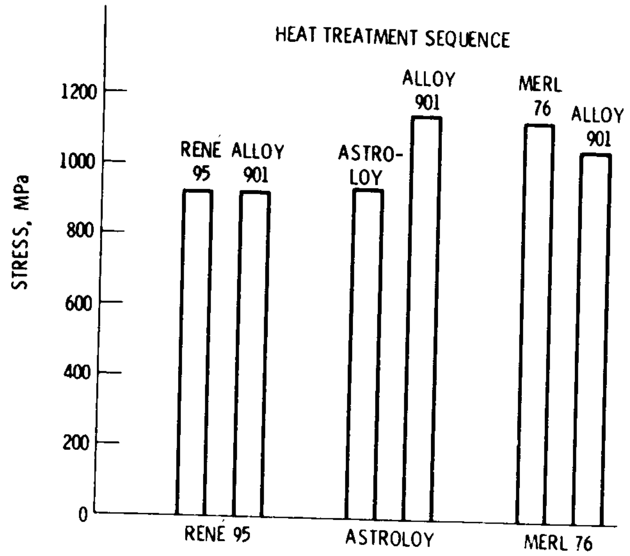


Figure 5. - Stress to rupture three superalloys in 100 hr at 650 °C.

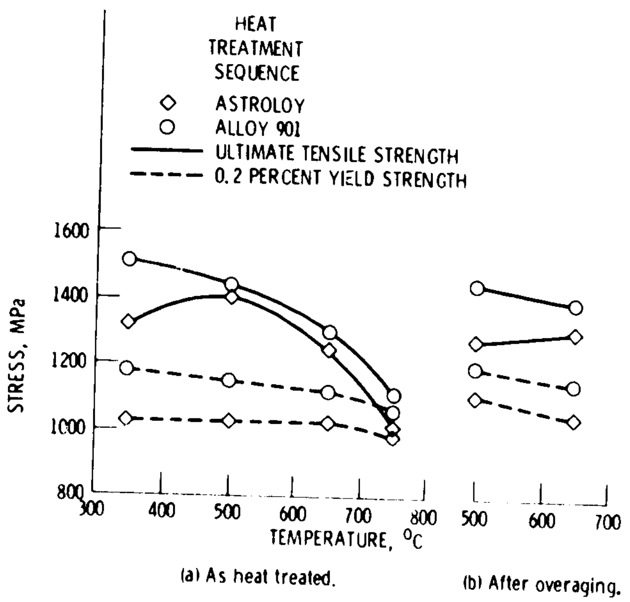
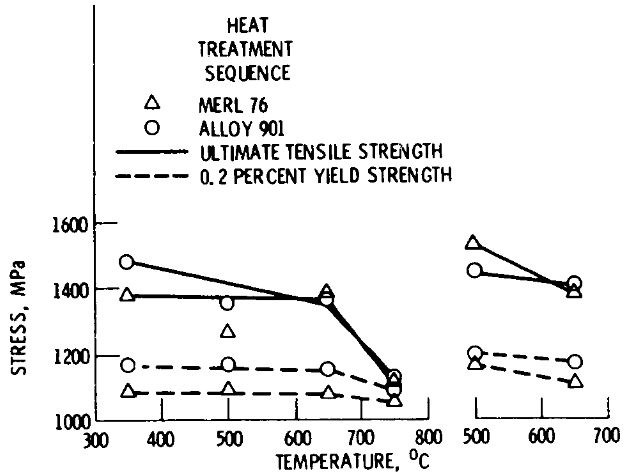
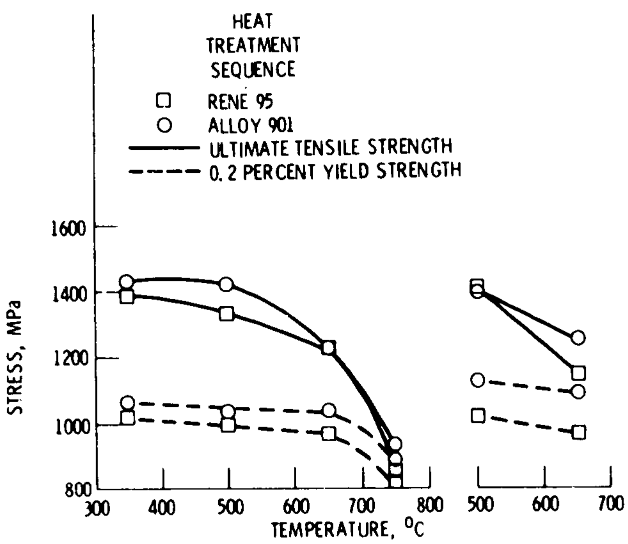


Figure 6. - Tensile properties of Astroloy.



(a) As heat treated. (b) After overaging.

Figure 7. - Tensile properties of MERL 76.



(a) As heat treated. (b) After overaging.

Figure 8. - Tensile properties of mixtures of René 95 and Alloy 901.

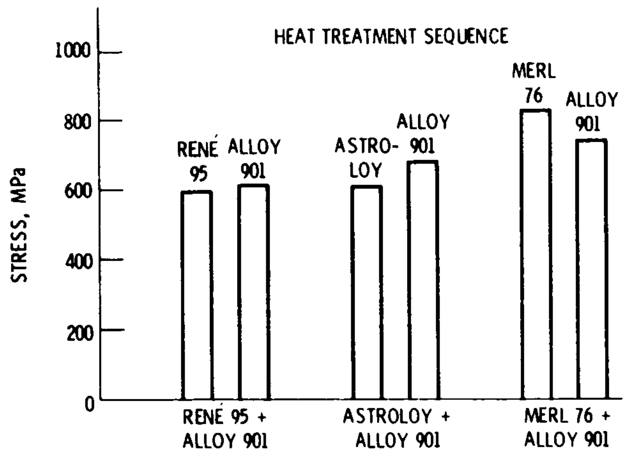


Figure 9. - Stress to rupture superalloy mixtures in 100 hr at 650 °C.

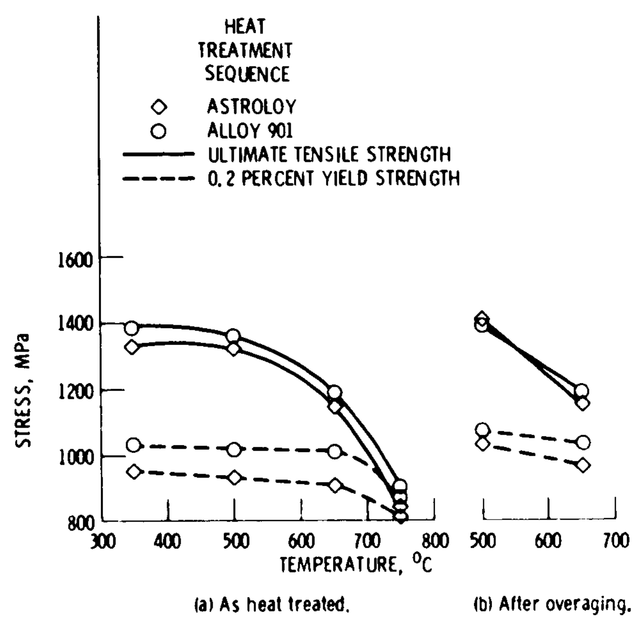


Figure 10. - Tensile properties of mixtures of Astroloy and Alloy 901.

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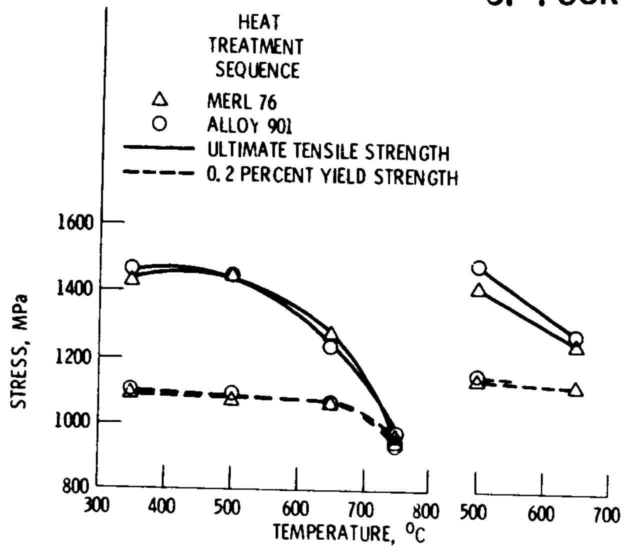
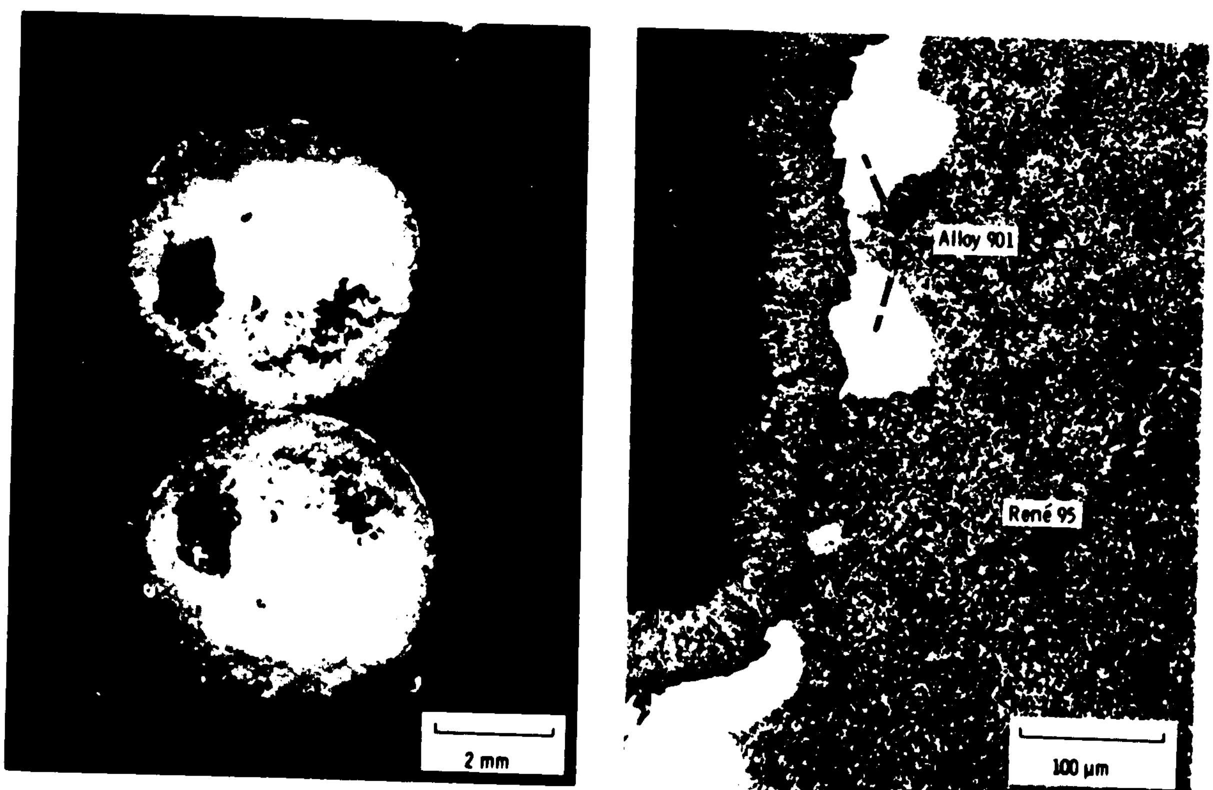


(a) As heat treated. (b) After overaging.

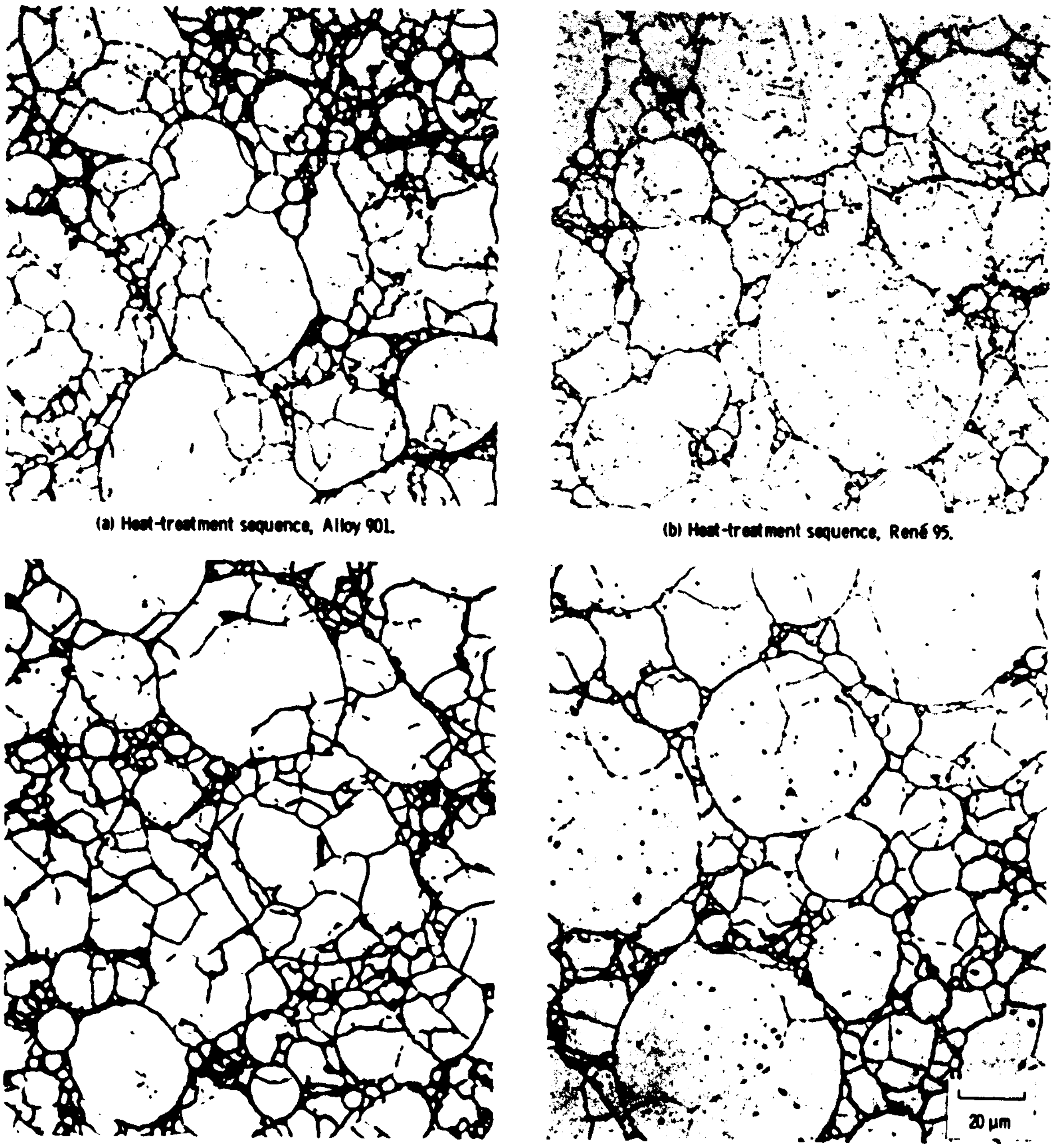
Figure 11. - Tensile properties of mixtures of MERL 76 and Alloy 901.



(a) View of failure traversing alloy 901 except in dark area where René 95 is exposed.

(b) Longitudianal section location where failure extends into both locations.

Figure 12. - Layered combination of René 95 and Alloy 901 failed in stress rupture test at 650 °C.



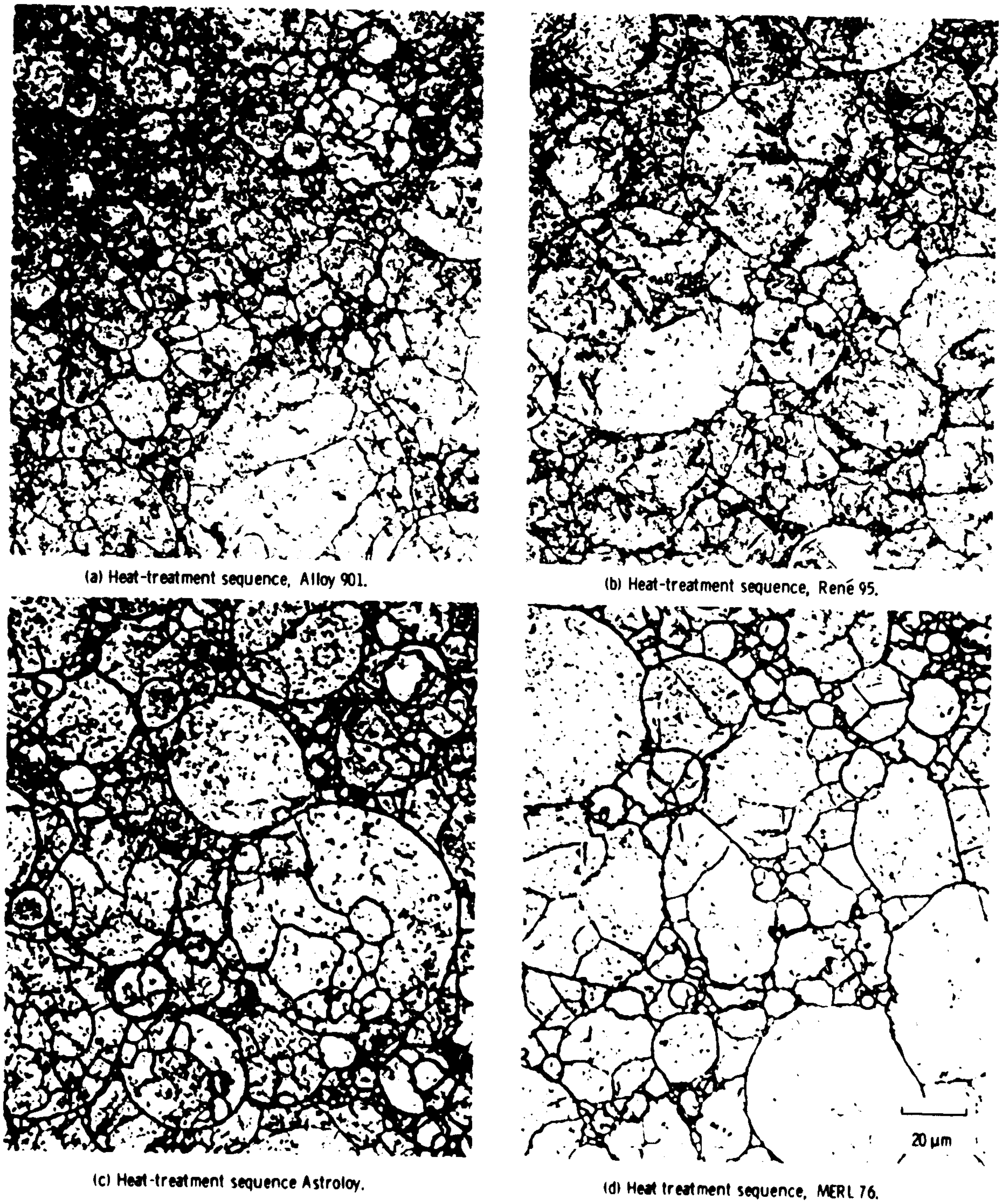
(a) Heat-treatment sequence, Alloy 901.

(b) Heat-treatment sequence, René 95.

(c) Heat-treatment sequence, Astroloy.

(d) Heat-treatment sequence, MERL 76.

Figure 13. - Microstructure of heat treated Alloy 901.



(a) Heat-treatment sequence, Alloy 901.

(b) Heat-treatment sequence, René 95.

(c) Heat-treatment sequence Astroloy.

(d) Heat treatment sequence, MERL 76.

Figure 14. - Microstructures of HIP-PM Alloy 901 after overaging.

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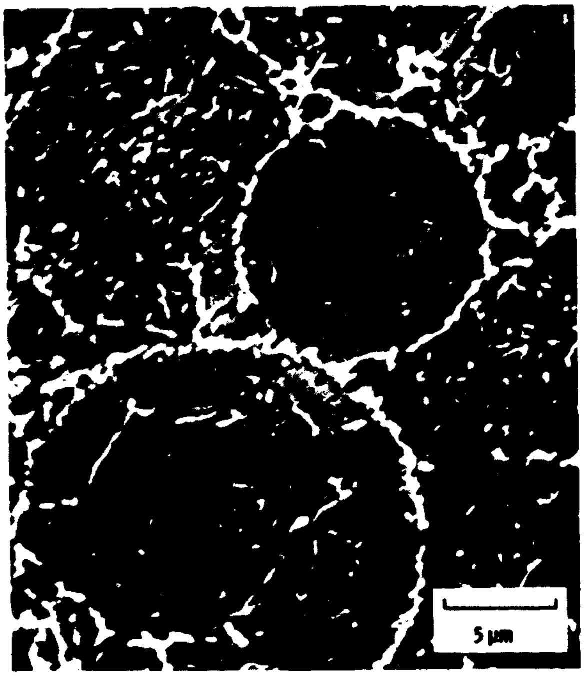
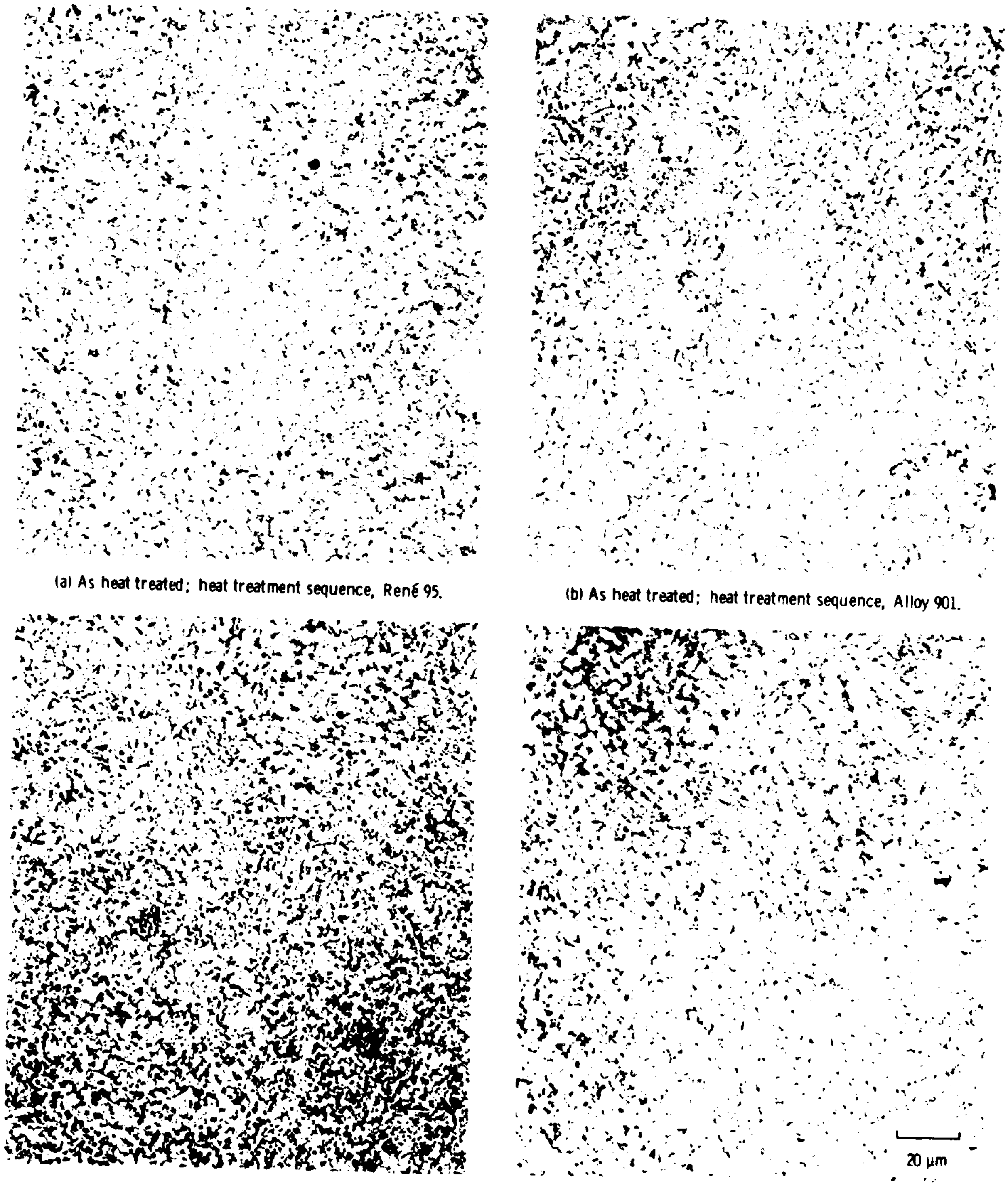


Figure 15. - Higher magnification of overaged Alloy 901 with Alloy 901 heat treatment. Light colored particles are Ni_3Ti.



(a) As heat treated; heat treatment sequence, René 95.

(b) As heat treated; heat treatment sequence, Alloy 901.

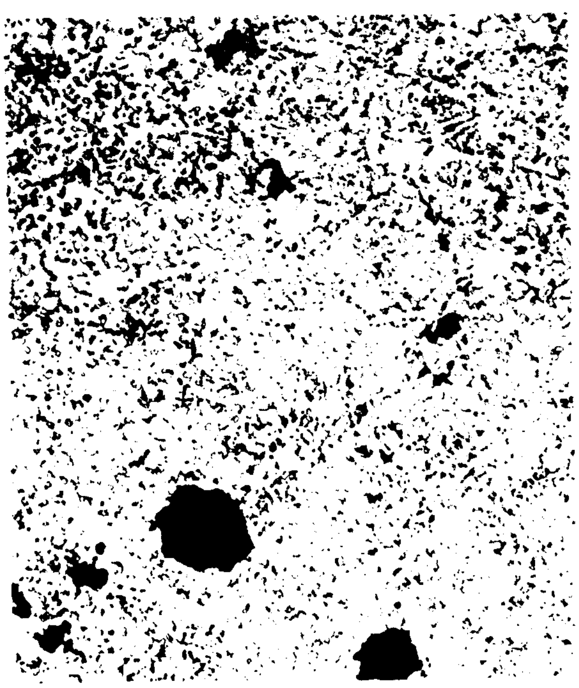
(c) After overaging; heat treatment sequence, René 95.

(d) After overaging; heat treatment sequence, Alloy 901.

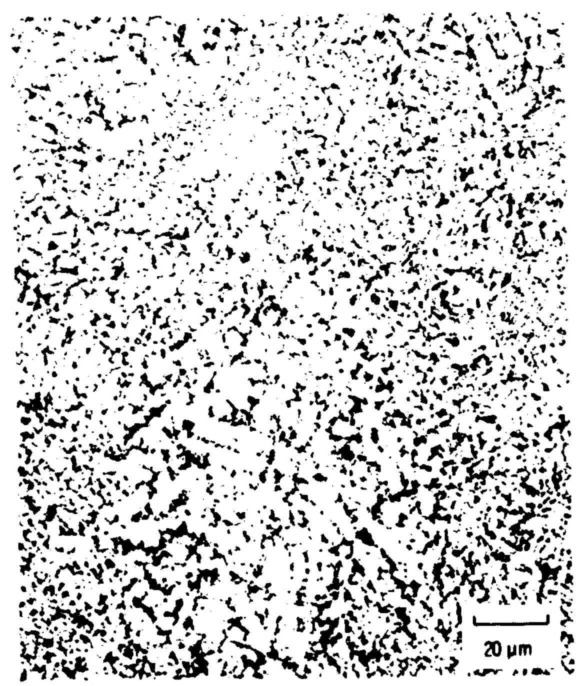
Figure 16. - Microstructures of René 95.

(a) As heat treated; heat treatment sequence, Astroloy.

(b) As heat treated; heat treatment sequence, Alloy 901.

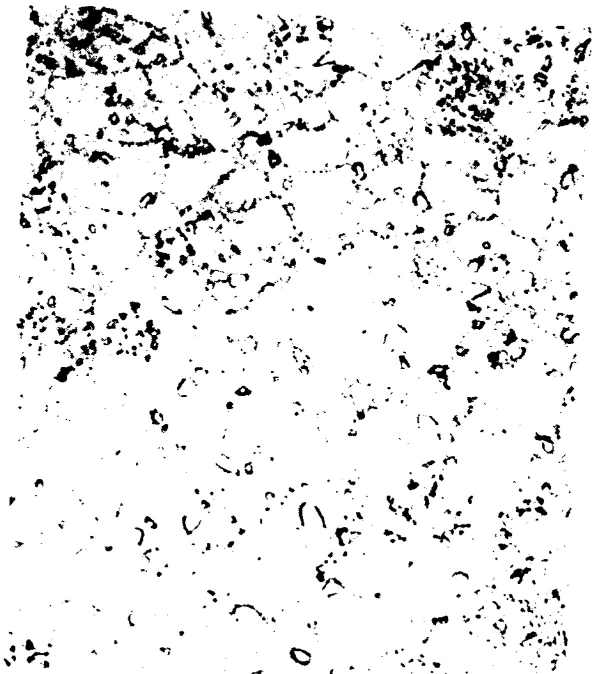


(c) After overaging; heat treatment sequence, Astroloy.



(d) After overaging; heat treatment sequence, Alloy 901.

Figure 17. - Microstructures of Astroloy. (Porosity in (c) was caused by container leak during hot isostatic pressing.)



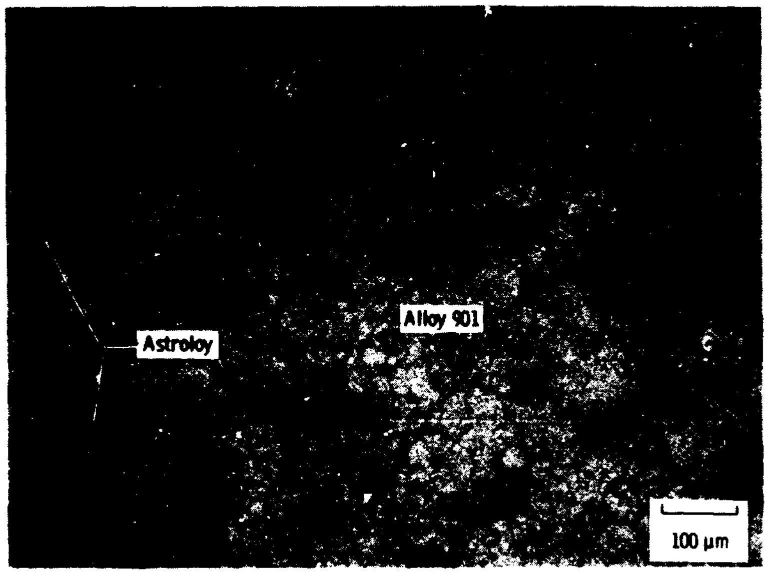
(a) As heat treated; heat treatment sequence, MERL 76.

(b) As heat treated; heat treatment sequence, Alloy 901.

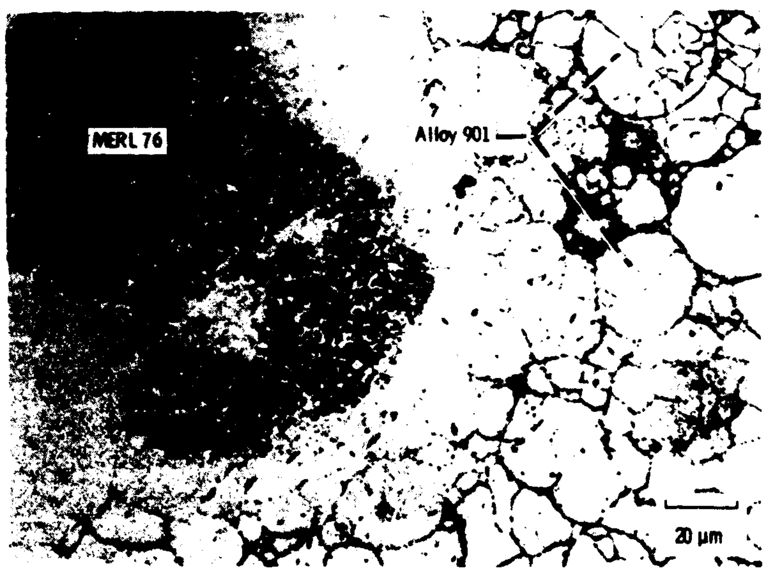
(c) After overaging; heat treatment sequence, MERL 76.

(d) After overaging; heat treatment sequence, Alloy 901.

Figure 18. - Microstructures of MERL 76.



(a) Astroloy and Alloy 901 given Astroloy heat treatment.



(b) MERL 76 and Alloy 901 given Alloy 901 heat treatment.

Figure 19. - Microstructures of mixed alloys.

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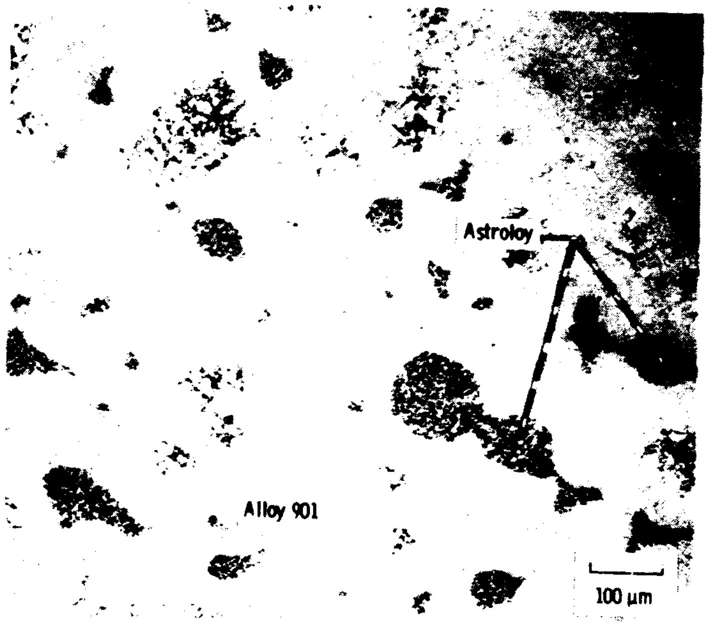
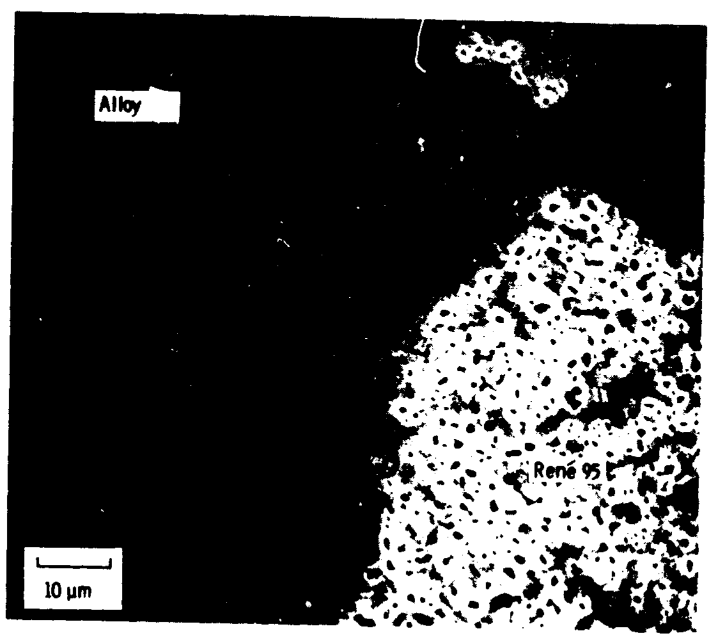


(a) Astroloy and Alloy 901 given Alloy 901 heat treatment.



(b) Rene 95 and Alloy 901 given René 95 heat treatment.

Figure 20. - Microstructures of overaged mixed alloys.

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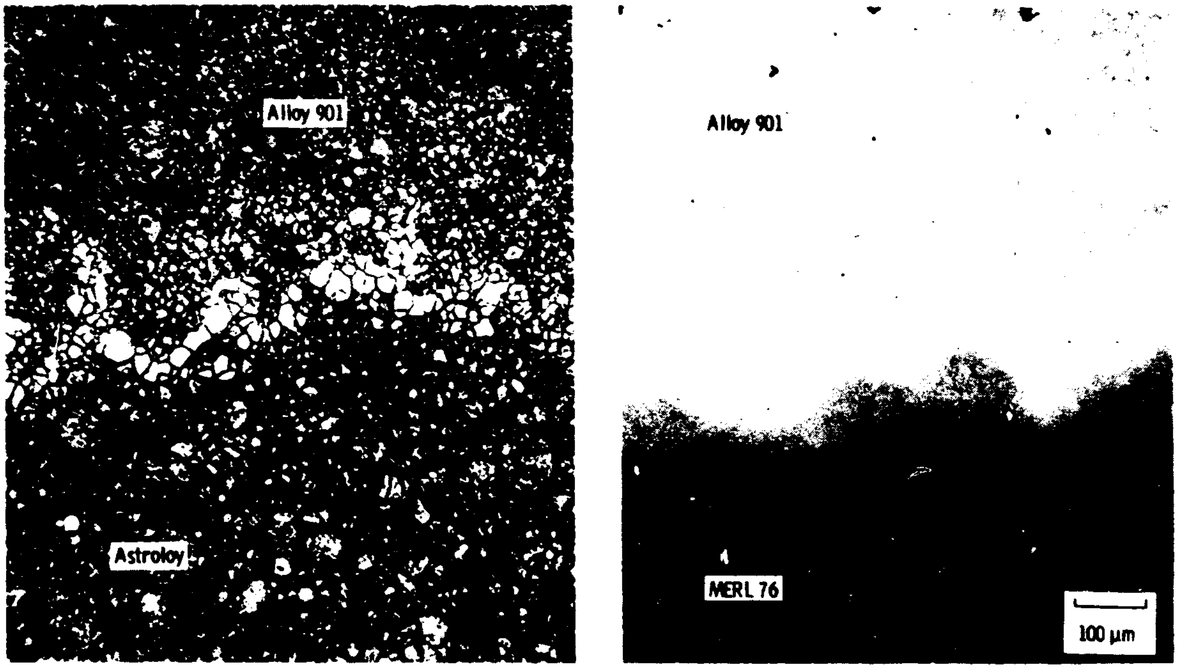

(a) Alloy 901 and Astroloy given Astroloy heat treatment.

(b) Alloy 901 and MERL 76 given MERL 76 heat treatment and aged.

Figure 21. - Microstructure of joint between two alloys.

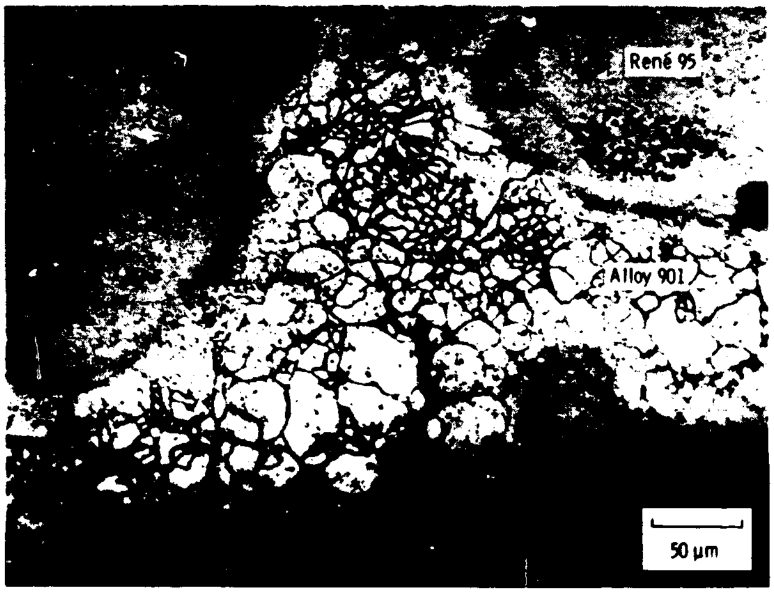

Figure 22. - Incipient fracture at 650 °C in a tensile specimen of mixed René 95 and Alloy 901. Heat treatment sequence, Alloy 901. Crack follows grain and prior particle boundaries in Alloy 901.

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16. Abstract

Dual alloy combinations have potential for use in aircraft engine components such as turbine disks where a wide range of stress and temperature regimes exists during operation. Such alloy combinations may directly result in the conservation of elements which are costly or not available domestically. Preferably, a uniform heat treatment yielding good properties for both alloys should be used. Dual alloy combinations of iron rich Alloy 901 with nickel-base superalloys René 95, Astroloy, or MERL 76 were hot isostatically pressed from prealloyed powders. Individual alloys, alloy mixtures, and layered alloy combinations were given the heat treatments specified for their use in turbine disks or appropriate for Alloy 901. Selected specimens were overaged for 1500 hr at 650 °C. Metallographic examinations revealed the absence of phases not originally present in either alloy of a combination. Mechanical tests showed adequate properties in combinations of René 95 or Astroloy with Alloy 901 when given the Alloy 901 heat treatment. Combinations with MERL 76 had better properties when given the MERL 76 heat treatment. The results indicate that these combinations are promising candidates for use in turbine disks.

17. Key Words (Suggested by Author(s))
Dual alloy; Nickel base alloy; High temperature properties; Microstructure; Metal joining; Powder metallurgy; Thermal stability; Heat treatments; Alloy 901; René 95; MERL 76; Astroloy

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