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DEVELOPMENT STUDY OF COMPOSITIONS FOR ADVANCED WROUGHT NICKEL-BASE SUPERALLOYS

by

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16. Abstract

Using NASA IIb as a base composition, the effects of five key elements (carbon, tungsten, tantalum, aluminum, and hafnium) on resultant properties were investigated in an effort to optimize the composition and derive new wrought high temperature alloys with improved strength characteristics. A total of nineteen compositions were melted, extruded, and rolled to bar stock using thermomechanical processing. Both full and partial solution heat treatments were developed for the compositions. Tensile properties from room temperature to 1800°F (982°C), stress and creep rupture properties to 1800°F (982°C), and thermal stability characteristics were evaluated. NASA IIb-7 exhibited the best response to the partial solution heat treatment for optimum properties up to 1200°F (649°C). The alloy contained 0.13C, 9.0 Cr, 9.0 Co, 2.0 Mo, 7.5 W, 10.0 Ta, 3.5 Al, 0.75 Ti, 0.02 B, 0.10 Zr, 0.50 V, 1.0 Hf, and balance nickel. Another promising composition, designated NASA IIb-11, for full solution heat treatment applications at 1400°F (760°C) and above contained 0.13 C, 9.0 Cr, 9.0 Co, 2.0 Mo, 7.5 W, 7.0 Ta, 4.5 Al, 0.75 Ti, 0.02 B, 0.10 Zr, 0.50 V, 1.0 Hf, and balance nickel. Both alloys will require additional property studies as prerequisities to engine service and may offer excellent potential for production scale-up.

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FOREWORD

The work described herein was conducted over a 19 month period by the Research and Development Department of the Universal-Cyclops Specialty Steel Division, Bridgeville, Pennsylvania, under NASA Contract NAS 3-14309. The contract was administered under the management of the NASA Project Manager, Mr. F. H. Harf, Materials and Structures Division, NASA Lewis Research Center. Mr. S. G. Young served as the NASA Research Advisor.

The Project Engineer for the program was Mr. W. B. Kent of Universal-Cyclops Specialty Steel Division. Mr. L. W. Lherbier served as Program Supervisor, and technical assistance was provided by Mr. H. L. Black.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF TABLES

LIST OF TABLES (continued)

LIST OF TABLES (continued)

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

I. SUMMARY

The object of this program was to optimize the chemical composition of NASA IIb for the purpose of developing advanced wrought nickel-base alloys for use in advanced gas turbine engines. The program was divided into two tasks. The effects of five key elements (carbon, tungsten, tantalum, aluminum, and hafnium) on resultant properties were statistically determined in Task I. Based on this statistical analysis, two new compositions were formulated for additional studies in Task II. One of the new alloys, NASA IIb-L, was formulated based on optimum mechanical properties at low operating temperatures [up to 1200°F (649°C)]; while the second alloy, NASA IIb-H, was designed to attain optimum property capabilities at elevated temperatures [1400°F (760°C) and above].

Seventeen alloy compositions were formulated for the Task I optimization studies. These alloys were hot worked first by extrusion, and then by rolling to bar stock. The rolling was conducted at low working temperatures to determine the response of the alloys to thermomechanical processing. In addition, both full and partial solution heat treatments were developed for each alloy. Testing was conducted on material in the extruded condition subjected to a full solution heat treatment, and on material in the extruded plus rolled condition subjected to both full and partial solution heat treatments. These tests included tensile tests over the range from room temperature to 1800°F (982°C) and stress rupture tests at a variety of conditions from 1200°F/175,000 psi (649°C/1207 MN/m^2) to 1800°F/25,000 psi (982°C/172 MN/m^2). The alloys were also subjected to a thermal exposure at 1600°F (871°C) for 1500 hours to determine the effects of this treatment on mechanical properties and microstructure. The results of this task evolved two alloys with excellent capabilities. NASA IIb-7 displayed outstanding properties up to 1200°F (649°C) in the extruded plus rolled condition with a partial solution heat treatment; in fact, the strengths achieved over the temperature range reflected improvements at least 20 percent in excess of the strongest commercially available alloy. The alloy displayed a room temperature ultimate tensile strength of 298,000 psi (2060 MN/m^2) and a strength at 1200°F (649°C) of 258,000 psi (1780 MN/m^2) while maintaining ductility of nearly ten percent. The stress rupture life of NASA IIb-7 at 1200°F/175,000 psi (649°C/1207 MN/m^2) was 250 hours, or approximately ten times the life of the best alloy commercially available. NASA IIb-11 exhibited exceptional properties at 1400°F (760°C) and above in the extruded and rolled condition with a full solution heat treatment. The ultimate tensile strength at 1400°F (760°C) was 185,000 psi (1275 MN/m^2) and at 1800°F (982°C) was 80,000 psi (550 MN/m^2), representing about a 25 percent improvement over current alloys. NASA IIb-11 displayed a stress rupture life at 1400°F/90,000 psi (760°C/621 MN/m^2) of 510 hours - five times longer than the best commercially available alloy. Its rupture life of 63 hours at 1800°F/25,000 psi (982°C/172 MN/m^2) was 40 percent better than any alloy now in use. Although the alloy did exhibit thermal instability, indications are that this condition can be remedied by only a slight chemistry modification.

Based on the Task I statistical analysis, two alloys were formulated for additional study in Task II. The general processing and testing sequence described for Task I was similar for Task II, although creep rupture testing was added for Task II. The results of the Task II studies indicated that the computer predicted properties were not achieved for alloys NASA IIb-L and IIb-H. In fact, their overall properties were not as good as those displayed by the two previously mentioned Task I alloys, NASA IIb-7 and IIb-11.

II. INTRODUCTION

Although turbine engine technology has grown tremendously during its nearly thirty year existence, recent advances have been seriously restricted due to materials limitations. Engine designers have sought to attain thrust increases by increasing operating temperatures within the hot sections of engines. However, current materials are unable to exhibit the combination of properties required for extended service at these increased temperatures. As a result, further significant advancement in aircraft engine technology is dependent upon: 1) the development of design criteria resulting in higher thrusts while maintaining current operating temperatures, 2) the development of advanced materials capable of achieving improved properties at current operating temperatures, or 3) the development of advanced materials capable of maintaining the current combination of properties at higher operating temperatures.

The ability of an alloy to exhibit a wide variety of excellent properties (depending on the method of processing and heat treatment) is of extreme importance in today's aerospace industry. The numerous companies involved in engine design each have achieved increased thrust capabilities by employing a variety of design concepts. For example, one major engine producer has designed its engines to operate at rather low temperatures - only up to 1200°F (649°C) in the hot section. Accordingly, this manufacturer is striving for wheel and disc alloys which exhibit very high 1200°F (649°C) strength properties. On the other hand, other major producers have designed their engines to achieve increased thrusts by increasing operating temperatures to the area of 1400°F (760°C) in the hot section. Still others would like to further increase these temperatures to the 1500° to 1600°F (816° to 871°C) range. Also, as operating temperatures are increased, blade and vane temperatures will be increased beyond their current 1800°F (982°C) limit. This wide variety of design concepts and property requirements illustrates the demand for versatile alloys.

In exploring the capabilities of current alloys, it is apparent that a variety of heat treatments and processing methods have been developed to optimize the properties of an alloy for a given application. For example, processing at low working temperatures (i.e., thermomechanical processing) is employed in conjunction with a partial solution heat treatment (below the recrystallization temperature) to obtain good properties in the range from room temperature to 1200°F (649°C). Tensile properties are maintained beyond 1200°F (649°C) for most alloys; however, stress rupture properties suffer as a result of the so called "superplastic" characteristics effected by the heat treatment. On the other hand, a full solution heat treatment is employed when the emphasis is on higher temperature applications such as 1400°F (760°C) and above. Although tensile properties are somewhat lower as compared with partial solution heat treated material, this treatment results in improved stress rupture properties at elevated temperatures. The response of an alloy to both of these processing methods determines its versatility.

One of the most promising and versatile alloy compositions investigated to date is NASA IIb. The original base composition of NASA IIb is shown below:

Chemical Composition (weight percent) for:

C	Cr	Co	Mo	W	Ta	Al	Ti	B	Zr	V	Hf	Ni
0.13	10.0	10.0	2.0	5.5	8.0	4.5	1.0	0.02	0.03	1.0	1.0	Balance

The alloy was originated during NASA Contract NAS3-7267 completed by TRW in 1967.[1] A subsequent contract, NAS3-11155, conducted by Universal-Cyclops Specialty Steel Division in 1970 resulted in the selection of NASA IIb as offering the most potential of six experimental superalloys evaluated.[2] The alloy exhibited ultimate tensile strengths in excess of 210,000 and 180,000 psi (1449 and 1241 MN/m^2) at 1200° and 1400°F (649° and 760°C), respectively. The stress rupture characteristics of NASA IIb were also promising with the alloy displaying a rupture life in excess of 200 hours at 1400°F and 90,000 psi (760°C and 621 MN/m^2). However, the alloy in its original form was found to be thermally unstable after long time exposure at elevated temperatures.

This program was initiated to optimize the chemical composition of NASA IIb for the purpose of developing wrought nickel-base superalloys for use in advanced gas turbine engines. Specifically, the program was designed to further enhance the mechanical properties of NASA IIb and to investigate the versatility of experimental compositions formulated based on the NASA IIb alloy system. Another primary objective of the program was to eliminate the tendency of the parent alloy towards thermal instability after long time exposures.

In order to provide information concerning the effects of certain elements within the NASA IIb alloy system on mechanical properties, a statistical design was chosen as a basis for the formulation of experimental compositions. The selected design permitted an investigation of the effects of five elements (at two chemistry levels per element) on resultant properties. The elements chosen included carbon, tungsten, tantalum, aluminum, and hafnium; these specific elements and their individual chemistry levels were chosen to maintain a balance between further increasing strength and improving the thermal stability characteristics of the base alloy system.

The results of the statistical analysis were then used to formulate two compositions, each designed to achieve optimum properties according to its own specific heat treatment. One composition was directed towards optimum properties up to 1200°F (649°C) using a partial solution heat treatment; while the other was formulated to develop optimum properties at 1400°F (760°C) and above using a full solution heat treatment.

III. ALLOY SELECTION

Based upon the results of previous developmental work conducted under NASA Contract NAS3-11155, it was concluded that the NASA IIb composition offered the best strength potential of any wrought nickel-base alloy developed to date. Therefore, the alloy was chosen as the base composition for this program. In order to further optimize the alloy for strength capabilities, it was decided that a program directed towards a statistical analysis of the effects of several key elements on strength properties offered the greatest probability for success. A review of the elements contained in the NASA IIb alloy system in conjunction with the results of contract NAS3-11155 evolved three elements considered directly related to strength characteristics. These elements included tungsten, tantalum, and hafnium.

Of the six alloys evaluated under Contract NAS3-11155, NASA IIb was the strongest and exhibited the highest refractory metal content. Conversely, I5 was the weakest and displayed the lowest refractory metal content of the six alloys. The choice of the three previously mentioned elements was therefore based on the approach to further strengthen the alloy system by introducing larger concentrations of the most effective solid solution strengthening elements. These elements, with their large atomic diameters, offered the best potential for increasing the solid solution strengthening mechanism of the base composition.

One significant shortcoming of the NASA IIb base composition, as determined from previous work, was that of thermal instability.(2) The electron vacancy number (N_v) of the base composition was calculated at 2.47, which is slightly below the 2.50 value generally acknowledged as the limit beyond which thermal instability will result. [These N_v calculations were based on the method discussed by Woodyatt, Sims, and Beattie.(3)] However, this composition was found to be unstable due to the formation of a tungsten-rich mu phase during 1500 hours exposure at 1600°F (871°C). Although the specific thermal stability limits for the system were unknown, it was decided to design the majority of the experimental compositions to have N_v numbers below 2.47. This approach presented a problem as increases in the refractory metal content effected by increases in the three key elements resulted in even higher N_v numbers. Two methods were then adopted to further reduce N_v numbers while permitting additional percentage increases of the three strengthening elements.

The first method involved slight reductions in the base levels of four elements in the standard composition. The original base composition is listed in Table 1, in addition to the four modifications. The elements reduced included chromium and cobalt which were decreased from 10.0 to 9.0 percent, titanium from 1.0 to 0.75 percent, and vanadium from 1.0 to 0.5 percent. These reductions resulted in an overall decrease in the N_v number from 2.47 to 2.18, thereby permitting additional increases in refractory element content.

The second method for maintaining lower N_v numbers involved the selection of carbon and aluminum as two additional variable elements. While tungsten, tantalum, and hafnium were evaluated at increasing levels causing increased N_v numbers, the evaluation levels for carbon and aluminum were chosen to effect decreased N_v numbers. The two evaluation levels for carbon included the base level of 0.13 percent and an upper level of 0.25 percent; the levels for aluminum included the base level of 4.5 percent and a lower level of 3.5 percent. This approach towards higher carbon and lower aluminum was chosen to offset the poor workability characteristics imparted by the increased refractory metal content (tungsten, tantalum, and hafnium).

With respect to the evaluation limits for the solid solution strengthening elements, tungsten levels were selected at 4.5 and 7.5 percent, tantalum at 7.0 and 10.0 percent and hafnium at 1.0 and 2.5 percent. These levels were derived on the basis of balancing the compositions so N_v numbers for the majority of compositions were below the 2.47 value previously found to display instability.

The statistical design used for formulating the seventeen alloy compositions is outlined in Appendix A of this report. Basically, the design is a one-half replicate of a five variable factorial set, with each of the five variables investigated at an upper and a lower level. Sixteen heats were required for the design; however, the addition of a seventeenth design center heat permitted a third evaluation level for each variable element at the center point of the upper and lower levels. The aim chemical analyses for the seventeen heats are listed in Table 2.

IV. PROCEDURE

A. Task I - Alloy Screening

1. Materials

Virgin raw materials were used for all heats melted to minimize the level of impurity elements and to reduce their effects on resultant properties. A minimum purity level of 99.9 percent was specified for all alloying elements.

2. Melting

Each of the seventeen alloy compositions was double vacuum melted in 50 pound (22.7 kg) quantities. The initial melting operations were conducted in vacuum induction furnaces, and the electrodes were then vacuum consumable-arc remelted to obtain the final cast product.

The first step for vacuum induction melting included melting of the main charge which consisted of nickel, chromium, tantalum, molybdenum, tungsten, and one-half of the total carbon addition. After the initial melt-down, cobalt and the remainder of the carbon were added. The bath was then allowed to cool and form a thin "skin" on the surface prior to the addition of the reactive elements, titanium and aluminum. After the titanium and aluminum were added, power was slowly increased allowing these elements to melt in slowly with a minimum of reaction. Zirconium and nickel-boron were then added along with hafnium and vanadium. Each heat was deoxidized by plunging magnesium into the bath after the temperature had stabilized at 2850°F (1566°C). The bath was then cooled to approximately 2750°F (1510°C), and the product was cast into 2-1/2 inch (0.063m) diameter electrodes.

With respect to remelting, the 2-1/2 inch (0.063 m) diameter round electrodes were vacuum consumable-arc remelted into two 3-1/8 inch (0.079 m) diameter ingots weighing approximately 25 pounds (11.4 kg) each.

3. Chemical Analyses

A one-half inch (0.013 m) slice was sectioned from each vacuum induction melted electrode for X-ray spectrographic analysis. The slices were also lathe turned to provide chips for wet chemical analysis. Carbon, boron, hafnium, and zirconium were analyzed by wet chemistry techniques; and, X-ray spectrographic techniques were employed to analyze the remainder of the elements.

4. As-Cast Hot Workability Studies

As-cast Gleeble hot workability studies were conducted on material from one 25-pound (11.4 kg) double vacuum melted ingot from each composition. A 2-1/2 inch (0.063 m) thick slice was sectioned from the top half of an ingot of each of the seventeen experimental compositions. Eight longitudinal Gleeble hot ductility specimens were sectioned and machined to the required dimensions of one-quarter inch (0.006 m) diameter and two inches (0.050 m) long. The test specimen configuration is illustrated in Figure 1. The eight specimens from each ingot were used to develop inherent ductility profiles for each alloy over the temperature range of 1850° to 2100°F (1010° to 1149°C). For these tests, the specimens were heated at a rate of 85°F (45°C) per second to the specified temperature in the hot working range, held for five minutes, and pulled in tension at a nominal strain rate of five seconds^{-1}. This strain rate approximates the rate of extrusion. Ultimate tensile strength and reduction of area were measured and recorded for each specimen. The ductility data were plotted versus temperature to provide an inherent ductility profile for each alloy in the cast condition.

5. Processing

a. Extrusion

The remaining piece from one 25-pound (11.4 kg) ingot and the two additional pieces from the second 25-pound (11.4 kg) ingot were used for the extrusions. The three pieces from each composition were turned to 2-1/2 inches (0.063 m) in diameter and canned in 1/2 inch (0.013 m) thick mild steel in preparation for extrusion at the Air Force Materials Laboratory (AFML), Wright-Patterson Air Force Base. A schematic representation of the type of container used is shown in Figure 2. The three canned pieces of each alloy composition were coated with a glass slurry, heated to the desired extrusion temperature, soaked for a minimum of one hour, and extruded to a canned diameter of 1-1/8 inches (0.028 m).

b. Rolling

Two of the three extruded bars from each composition were processed further by rolling. The bars were sectioned into approximately six inch (0.15 m) long pieces in preparation for rolling. No additional canning was required, as the cans applied prior to extrusion were still intact. The bars were rolled from a subcritical rolling temperature of 2025°F (1107°C) after soaking at temperature for about one-half hour. Rolling was conducted from the 1-1/8 inch (0.028 m) diameter starting size to one-half inch (0.013 m) diameter bars. The bars were rolled using 10 to 20 percent reductions per reheat with intermediate reheating at 2025°F (1107°C).

6. Heat Treatment Evaluation

a. Determination of Optimum Treatments

(1) Full Solution Heat Treatment-Extruded Plus Rolled Material

Evaluations were conducted to determine full solution heat treatments for the one-half inch (0.013 m) diameter as-extruded plus rolled material from each composition. Three optimum temperature cycles were determined to make-up each treatment. The optimum cycles included a full solution treatment, an intermediate aging treatment, and a final aging treatment.

Full solution treatments were determined by treating one-quarter inch (0.006 m) square specimens from each composition for two hours at both 2150°F (1177°C) and 2225°F (1219°C), and for two and four hours at 2250°F (1232°C). The specimens were then prepared for examination by optical microscope. Using these samples, an optimum full solution treatment was determined for each composition. The treatments were chosen based on the degree of carbide and gamma prime solutioning, and especially on grain size. Grain growth occurs as primary gamma prime and carbides are solutioned; and, a uniform grain size of approximately ASTM 5 to 6 was the desired aim in order to maintain a constant grain size in all compositions, thereby eliminating a variable in evaluating subsequent test results.

Optimum intermediate aging treatments were determined for each alloy in a similar manner. Small cubes sectioned from the extruded plus rolled bars were first solution treated according to the treatment derived from the above studies. Material representing each composition was subjected to intermediate aging treatments at 1900° and 1950°F (1038° and 1066°C) for two hours and at 1600°, 1650°, 1900°, and 1950°F (871°, 899°, 1038°, and 1066°C) for sixteen hours. These treatments were evaluated for each alloy by optical microscopy. The optimum treatments were determined based on the degree of gamma prime nucleation and on carbide precipitation.

Optimum final aging treatments were determined by subjecting small cubes to the optimum full solution and intermediate aging treatments determined above for each composition. The cubes were then subjected to final aging treatments at 1300° and 1400°F (704° and 760°C) for sixteen hours. Optimum final aging treatments were chosen for each alloy based on electron microscopy examination to establish gamma prime and carbide morphology.

(2) Full Solution Heat Treatment-Extruded Material

Full solution heat treatment studies were also conducted on 1-1/8 inch (0.028 m) diameter as-extruded material. The same three-cycle treatments were determined for each alloy as described above; however, due to the decreased amount of work as compared to the extruded plus rolled material, slightly lower solution treatment temperatures were required to achieve the desired grain size. The solution treatments evaluated included two hour treatments at 2150°, 2200°, 2225°, and 2250°F (1177°, 1204°, 1219°, and 1232°C). Intermediate and final aging treatments chosen for extruded material were the same as those selected above for extruded plus rolled material.

(3) Partial Solution Heat Treatment-Extruded Plus Rolled Material

Three-cycle partial solution heat treatments were developed for each of the alloys in the as-extruded plus rolled condition. The general treatment consisted of an intermediate conditioning treatment, followed by increasing the temperature to the partial solution treatment temperature, oil quenching, then final aging. The conditioning and final aging treatments chosen for each alloy were the same as those developed for the full solution heat treatment studies described above. Small cubes sectioned from the one-half inch (0.013 m) diameter as-extruded plus rolled material were subjected to partial solution treatments for one hour at 2000°, 2100°, and 2150°F (1093°, 1149°, and 1177°C) followed by oil quenching. These samples were examined metallographically and an optimum partial solution treatment was determined for each alloy based on the choice of a temperature approximately 50°F (28°C) below the recrystallization temperature for the given alloy.

b. Structural Examinations

Structural examinations were conducted to varying degrees on samples of each alloy in various heat treatment conditions. The examinations included optical metallography, electron microscopy, and X-ray phase analysis.

Two methods of sample preparation were employed in preparing samples for optical metallography. In preparing samples for screening studies to determine an optimum temperature from several trial treatments, all samples were first prepared by electropolishing and then etching in the following solutions, depending on the response of the material and the desired effect:

(1) 60 percent water
15 percent sulfuric acid
15 percent hydrofluoric acid
9 percent nitric acid
1 percent hydrogen peroxide

(2) 85 percent water
14 percent hydrochloric acid
1 percent hydrogen peroxide

These roughly prepared samples were examined and upon choosing the optimum treatments, quality samples were prepared. These quality samples were prepared by mechanical polishing through various grit abrasive papers and diamond polishing wheels. The general procedure for etching was the same as described above. Photomicrographs were taken representing each individual step of the full and partial solution heat treatments developed above.

Electron microscopy examinations were conducted on all samples subjected to final aging treatments in the full solution heat treated condition. The procedures involved mechanical polishing through a 600 grit silicon carbide abrasive followed by electrolytic polishing in a solution of perchloric acid in alcohol. Samples were etched in a variety of solutions, namely perchloric, hydrochloric, and sulfuric acids, to emphasize the desired structural characteristics. The polished and etched specimens were then single stage replicated using a one percent solution of parlodion in isoamylacetate. Shadowing was performed with chromium at an angle of approximately 15 degrees. All electron micrographs were taken at a magnification of 2500X and were photographically enlarged to 5000X.

X-Ray phase analyses were conducted on as-extruded material representing each composition in the full solution heat treated condition. The samples were prepared for electrolytic extraction by machining to a standard size, then sand blasting at low pressure. They were then cleaned electrolytically in a ten percent solution of hydrochloric acid in methanol for ten minutes. The samples were rinsed and extractions were conducted in a new solution of the same mixture. The extractions were conducted for one-half hour using a current density of approximately 0.25 amps per square inch (400 amps per square meter). The residues were cleaned in methanol, dried, mounted on glass slides and subjected to X-ray diffraction analyses to identify the phases present.

7. Mechanical Testing

All specimens for mechanical property testing were sectioned from either extruded or extruded plus rolled bar material, rough machined, radiographically inspected, heat treated by the optimum method, and finish machined and polished to the prescribed dimensions. The test specimen configurations and dimensions are illustrated in Figure 1. Tensile and stress rupture tests were included in the evaluation. Extruded material was tested in the full solution heat treated condition only, while extruded plus rolled material was evaluated in both the full and partial solution heat treated conditions.

a. Tensile Testing

Duplicate tensile tests were conducted on full solution heat treated extruded and extruded plus rolled material at room temperature, 1400°, and 1800°F (760° and 982°C). For partial solution treated extruded plus rolled material, only single tensile tests were conducted at 1800°F (982°C), and the remaining single test was conducted at 1200°F (649°C).

All tensile tests were conducted on a 50,000 pound (2270 kg) capacity Baldwin-Emery tensile testing machine. The specimens were pulled at a nominal strain rate of 0.005 minute^{-1} up to the 0.2 percent yield point, where the strain rate was increased to 0.05 minute^{-1}. The yield point was measured by use of a deflectometer. Special furnaces were employed for elevated temperature tests, and the specimens were held at temperature for a minimum of 20 minutes prior to testing.

b. Stress Rupture Testing

Duplicate stress rupture tests were conducted at 1400°F/90,000 psi and 1800°F/25,000 psi (760°C/620 MN/m^2 and 982°C/173 MN/m^2) for full solution heat treated extruded and extruded plus rolled material. For partial solution treated extruded plus rolled material, tests at 1200°F/175,000 psi (649°C/1207 MN/m^2) were conducted in addition to the 1400°F/90,000 psi (760°C/620 MN/m^2) tests.

All stress rupture testing was conducted on lever arm testing machines. The samples were loaded into the furnaces, heated to the desired temperature, and held for 15 minutes prior to applying the load. Rupture life was measured from the time the load was applied. Sample temperature was controlled to $\pm$ 5°F (3°C).

8. Thermal Stability Studies

a. Thermal Exposure

Specimens of extruded bars from each composition were subjected to their optimum full solution heat treatments and were then exposed for 1500 hours at 1600°F (871°C). The material exposed for each composition included two tensile specimens, one X-ray specimen and one micro specimen. The samples were enclosed in a protective package during the thermal exposure to prevent excessive oxidation or any type of outside contamination.

b. Tensile Testing

The tensile specimens representing each composition were removed from the furnace after the 1500 hour exposure, and were finish machined and polished to size. Duplicate room temperature tensile tests were conducted on the as-heat treated plus exposed material and the results were compared with those obtained previously on as-heat treated material with no thermal exposure.

c. Structural Examinations

The effect of the thermal exposure on microstructure was determined through optical and electron microscopy. Specimens were prepared as previously described.

Exposed material from each composition was also evaluated by X-ray analyses of extracted residues. These procedures were also detailed in a previous section.

The microstructural examinations and phase studies conducted on exposed material were compared to the results obtained previously for unexposed material to determine the effects of the exposure on structural characteristics.

9. Data Analysis

The results of the Task I mechanical property tests were subjected to multiple regression analyses for the purpose of selecting two alloys for Task II study. A description of the computer analysis and the results obtained is included in Appendix A of this report. Briefly, the properties obtained on extruded plus rolled material were used to formulate the two Task II alloys. The first alloy, IIb-H, was formulated based on optimum 1400°F/90,000 psi (760°C/621 MN/m^2) stress rupture life in the full solution heat treated condition. The second alloy, IIb-L, was derived based on optimum 1200°F (649°C) yield strength in the partial solution heat treated condition.

B. Task II - Alloy Improvement

1. Alloy Preparation

The two alloys selected for Task II study were double vacuum melted using the same methods described for the Task I alloys. Again, complete chemical analyses were obtained on both vacuum induction melted heats.

The two 25-pound (11.4 kg) ingots representing each composition were each sectioned in half. The resulting four pieces were canned to 2.92 inches (0.074 m) in diameter (Figure 2) and were extruded to 1-1/8 inch (0.028 m) diameter bars at the AFML. The temperatures and general extrusion procedures were the same as those conducted under Task I.

All of the extruded bar material obtained from each composition was sectioned and rolled to one-half inch (0.013 m) diameter bar stock using the Task I rolling procedures, incorporating thermomechanical processing through the use of a low rolling temperature.

2. Heat Treatment Evaluation

Heat treatment studies were conducted on the two Task II alloys in the extruded plus rolled condition only. A full solution heat treatment was determined for IIb-H, the Task II alloy chosen for high temperature applications; and a partial solution heat treatment was determined for IIb-L, the alloy chosen for low temperature applications. The procedures for deriving the optimum full and partial solution heat treatments were the same as those outlined in Task I.

In addition, structural evaluations were conducted on each alloy in the heat treated condition. These evaluations included optical and electron microscopy and X-ray diffraction studies.

3. Mechanical Testing

Mechanical test specimens were prepared as previously discussed. The samples were heat treated according to the optimum methods developed for each alloy. Tensile tests (both smooth and notched), stress rupture tests, and creep rupture tests were included in this evaluation.

a. Tensile Testing

Smooth tensile tests were conducted in duplicate at room temperature, 1200°, 1400°, 1600°, and 1800°F (649°, 760°, 871°, 982°C) for IIb-H, the full solution heat treated Task II alloy. Also, duplicate notched tests were conducted at room temperature, 1400° and 1800°F (760° and 982°C).

For the partial solution treated Task II alloy, IIb-L, smooth tests were conducted at room temperature, 1200°, 1300°, and 1400°F (649°, 704°, and 760°C); and notched tests were conducted at room temperature and 1200°F (649°C).

The procedures for tensile testing were previously discussed.

b. Stress Rupture Testing

Duplicate stress rupture tests were conducted on full solution heat treated IIb-H at 1400°F/90,000 psi (760°C/621 MN/m^2), 1500°F/70,000 psi (815°C/483 MN/m^2), 1600°F/55,000 psi (870°C/379 MN/m^2), and 1800°F/25,000 psi (982°C/173 MN/m^2).

For partial solution heat treated IIb-L, tests were conducted at 1200°F/175,000 psi (649°C/1207 MN/m^2), 1300°F/125,000 psi (704°C/862 MN/m^2), and 1400°F/90,000 psi (760°C/621 MN/m^2).

The stress rupture test procedure was also discussed in a previous section.

c. Creep Rupture Testing

Samples for creep rupture testing were machined and polished to size as illustrated in Figure 1. The samples were tested on lever arm testing machines. The procedure involved loading the specimens into the furnace, heating to the desired temperature, holding 15 minutes and applying the load. Creep measurements were obtained with extensometers. Time to 0.2 percent creep was monitored for each sample beginning when the load was applied. The unit was also attached to a recorder, and the creep rate versus time was recorded for each sample.

Creep tests were conducted at 1400°F/90,000 psi (760°C/621 MN/m^2) for full solution heat treated IIb-H, while testing was conducted at 1000°F/160,000 psi (538°C/1103 MN/m^2) for partial solution heat treated IIb-L.

4. Thermal Stability Studies

Samples of IIb-H were subjected to 1500 hours exposure at 1600°F (871°C) and samples of IIb-L were subjected to 1500 hours exposure at 1300°F (704°C) in the same manner as described under the Task I procedure. After exposure, both alloys were evaluated using room temperature tensile tests, optical and electron microscopy and X-ray diffraction analyses to determine the effect of the exposure on mechanical and structural properties.

V. RESULTS AND DISCUSSION

A. Task I - Alloy Screening

1. Melting

Vacuum induction melting, casting and consumable-arc remelting of the seventeen compositions proceeded well. None of the compositions required deviations from the standard melting procedures previously established for alloys of this type.

2. Chemical Analyses

The alloy designations, heat numbers, and aim and actual chemical compositions for the seventten Task I heats are listed in Table 3. The very high alloy content of the compositions suggested probable deviations from standard element recovery values; however, these standard values proved to be quite accurate and all heats were within the range of normal weight percent deviation.

3. As-Cast Hot Workability Studies

The results of the Gleeble hot workability tests conducted on the seventeen alloys in the as-cast condition are summarized in Table 4. The inherent ductility profile for each alloy was determined from these data by plotting reduction of area versus test temperature. The resultant curve gives the optimum hot working temperature and the widest possible hot working range for the given alloy. An example of such a curve is illustrated in Figure 3 for IIb-3. This curve indicates a very narrow hot working range snd suggests an optimum working temperature in the area of 1900°F (1038°C). This curve is quite representative as similar curves were obtained by plotting the data for the other alloys.

The narrow hot working ranges and the exceptionally low optimum hot working temperatures suggested for these alloys are similar to the results obtained in previous work.(2) During the course of this previous work, extrusions were attempted at the low working temperatures suggested from the Gleeble data and the extrusions were not successful. However, extrusions conducted at higher temperatures [i.e., 2100°F (1149°C)] did prove successful although in direct conflict with the Gleeble inherent ductility data. As a result, the temperatures chosen for extrusion of the seventeen Task I alloys were based on past experience, in addition to the Gleeble-determined nil ductility point. Past work indicated a correlation between the zero or nil ductility point and the optimum working temperature for as-cast material.

4. Processing

a. Extrusion

The extrusion of the canned ingots from 2.92 inches (0.135 m) in diameter at the Air Force Materials Laboratory proceeded well. Slight nose and tail tearing was experienced for IIb-14, IIb-15, and IIb-16; while the extruded bars representing the remaining compositions were not damaged. It is noted that a portion of the mild steel can approximately 1/16 inch (0.002 m) thick still surrounded each billet after the extrusion.

It should also be noted that the good experience during extrusion from a 2100°F (1149°C) temperature was in direct conflict with the Gleeble data. Similar experience on the original as-cast IIb composition was noted previously. As shown in Figure 3, the 2100°F (1149°C) working temperature appears to offer little likelihood for success. However, as was the case in the previous work, a combination of the nil ductility point and the optimum working temperature established from previous experience resulted in a reliable temperature choice.

b. Rolling

The desired amount of material from each composition was successfully rolled from the as-extruded size [approximately 1-1/8 inches (0.028 m)] to one-half inch (0.013 m) bar stock with little difficulty. The only compositions to exhibit difficulty were IIb-13, IIb-14, IIb-15, and IIb-16. The soaking times during reheating were minimized to eliminate excessive oxidation and decomposition of the can. It was noted that surface cracks were initiated on bars with cans which were permitted to deteriorate. However, with the exception of the compositions noted above, the workability of the alloys at the lower hot working temperature of 2025°F (1107°C) was rated good.

5. Heat Treatment Evaluation

a. Determination of Optimum Temperatures

(1) Full Solution Heat Treatment-Extruded Plus Rolled Material

Three cycle full solution heat treatments consisting of a full solution treatment, an intermediate aging treatment and a final aging treatment were determined for one-half inch (0.013 m) diameter extruded plus rolled material from each composition. The optimum treatments developed for each alloy are summarized in Table 5.

Full solution treatments in the area of 2225° to 2250°F (1219° to 1232°C) for two or four hours were required to achieve the desired degree of carbide and gamma prime solutioning and grain size. The target grain size of ASTM 5 to 6 was achieved for each of the alloys. An example of the effect of various full solution treatments on ASTM grain size is shown in Figure 4 for IIb-17. In this case, changing the solution treatment conditions from a two hour treatment at 2150°F (1177°C) to a four hour treatment at 2250°F (1232°C) resulted in an increase in the grain size from recrystallization to ASTM 4 to 5. For IIb-17, the optimum full solution treatment chosen was a two hour treatment at 2250°F (1232°C).

An optimum intermediate aging treatment of 1600°F (871°C) for 16 hours was chosen for each of the alloys based on the degree of grain boundary carbide precipitation and on gamma prime nucleation. In general, the 1650°F (899°C) treatment for 16 hours resulted in excessive grain boundary carbide precipitation; and the treatments at 1900° and 1950°F (1038° and 1066°C) for either two or four hours resulted in overaging and agglomeration of the gamma prime particles. An example of gamma prime overaging is shown in Figure 5 for IIb-8, as compared with the optimum treatment. As a result, the treatments causing excessive carbide precipitation or gamma prime overaging were avoided due to their undesirable structural effects.

(2) Full Solution Heat Treatment-Extruded Material

Three cycle full solution heat treatments were also selected for 1-1/8 inch (0.028 m) diameter extruded material from each composition. The first cycle of the treatment, the full solution treatment, was chosen individually for each alloy; however, the intermediate and final aging treatments selected were the same as those derived for the extruded plus rolled material. The full solution heat treatment formulated for each composition in the extruded condition is listed in Table 6. The full solution treatment temperatures required to achieve the ASTM 5 to 6 grain size were slightly lower than those required for solutioning the extruded plus rolled material. This indicates that the low temperature rolling imparted characteristics to the material which require higher temperatures to effect the same degree of solutioning and grain growth. The full solution temperatures ranged from two hour treatments at 2225° to 2250°F (1219° to 1232°C).

(3) Partial Solution Heat Treatment-Extruded Plus Rolled Material

For the partial solution heat treatment cycles, a partial solution treatment was determined for each of the alloys and the conditioning and final aging treatments chosen were the same as those selected during the full solution heat treatment studies. The complete partial solution heat treatments selected for each of the alloys is summarized in Table 7. A partial solution treatment at 2000°F (1093°C) for one hour was chosen for each of the alloys with the exception of IIb-4 which required a treatment at 1950°F (1066°C) for one hour to achieve the desired results. Examples of the effects of increasing partial solution treatment temperatures on microstructure are shown in Figure 7 for IIb-7. As the temperature is increased from 2000°F (1093°C) to 2100°F (1149°C), considerable gamma prime and carbide solutioning is evident. The optimum treatment chosen for IIb-7 was the 2000°F (1093°C) treatment, and the resulting microstructure after incorporating both the intermediate and final aging treatments into the cycle is illustrated in Figure 8.

b. Structural Examinations

Optical micrographs were taken for each alloy in a variety of heat treatment conditions. Some of these photomicrographs were presented in the previous sections. In addition, electron microscopy studies were also conducted for each alloy in the full solution heat treated condition for extruded and extruded plus rolled material, and in the partial solution heat treated condition for extruded plus rolled material. The results of these studies are summarized in Figures 9 and 10 for full solution treated IIb-7 and IIb-11, and in Figure 11 for partial solution treated IIb-7.

A very interesting feature of the full solution treated microstructures (Figures 9 and 10) was the gamma prime particle morphology. The particles dispersed throughout the matrix were extremely fine; in fact, they were much finer than those exhibited in other alloys of this type. The carbide morphology, on the other hand, was characteristic of alloys of this type. Massive MC-types were found randomly throughout the matrix in addition to finer matrix and grain boundary carbides.

As expected, due to the limited extent of solutioning achieved during a partial solution heat treatment, Figure 11 for partial solution heat treated IIb-7 typefies a very coarse microstructure. Large particles of coarse, undissolved gamma prime in addition to small and massive MC-type carbide particles and smaller M_6C type carbides dominate the microstructure. In addition, as shown in the micrograph taken at 10,000X, a fine precipitate of "second generation" gamma prime is evenly dispersed throughout the matrix between the coarse gamma prime and carbides. Slight evidence of recrystallized grain boundaries are also evident at the high magnification.

The results of the X-ray diffraction studies of residues extracted from full solution heat treated as-extruded material are summarized in Table 8. For all of the compositions, the major phase present was an MC-type carbide. In fact, two distinct MC-type carbides were detected in most alloys; and IIb-7 contained three distinct varieties. Several alloys also contained weak amounts of M_6C or $M_{23}C_6$ type carbides, and IIb-15 displayed some evidence of a mu phase formed during heat treatment.

6. Mechanical Testing

a. Tensile Testing

(1) Extruded Material-Full Solution Heat Treated

The tensile test results for each experimental composition in the extruded and full solution heat treated condition are summarized in

Tables 9, 10, and 11 for room temperature, 1400° and 1800°F (760° and 982°C) test temperatures, respectively.

With respect to room temperature tensile properties, the data for the five best Task I alloys are illustrated in Figure 12. The best average ultimate tensile strength was exhibited by IIb-8 at 222,000 psi (1530 MN/m^2); IIb-12 displayed the best yield strength at 179,000 psi (1230 MN/m^2); while alloys IIb-8, IIb-11, and IIb-12 all exhibited good tensile ductility at about 11 percent. From Table 9, we can note that other alloys such as IIb-16 displayed good yield strength values; however, tensile ductility for these alloys was very low at approximately one percent. In general, ductility values for the highly-alloyed compositions IIb-13, IIb-14, IIb-15, and IIb-16 were consistently low.

Tensile data at 1400°F (760°C) for the five best Task I alloys are summarized in Figure 13. Strength levels were very close for each of the alloys. Ultimate tensile strength values ranged from 178,000 psi (1230 MN/m^2) for IIb-7 and IIb-12 to 186,000 psi (1280 MN/m^2) for IIb-8; and, yield strengths ranged from 152,000 psi (1050 MN/m^2) for IIb-17 to 158,000 psi (1090 MN/m^2) for IIb-12. Ductility values were also comparable in the seven to ten percent range, although they were slightly lower than the room temperature values.

Figure 14 depicts tensile data for the five alloys at 1800°F (982°C). Alloy IIb-11 displayed the best ultimate and yield strengths of the five alloys at 86,000 and 72,000 psi (593 and 496 MN/m^2), respectively. Ductility values for the alloys continued to decrease with increasing test temperature. Values ranged from about one to five percent at 1800°F (982°C) as opposed to greater than ten percent at room temperature.

(2) Extruded Plus Rolled Material-Full Solution Heat Treated

The results of tensile tests conducted on Task I extruded plus rolled material subjected to a full solution heat treatment are listed in Tables 12, 13, and 14 for room temperature, 1400° and 1800°F (760° and 982°C) properties, respectively. In addition, the data for the five best Task I alloys are summarized in Figures 15, 16, and 17 for comparison.

In general, the strength levels for the extruded plus rolled materials were slightly higher than those displayed by the extruded materials for most of the alloys. The most significant effect of the rolling was in improving tensile ductility. With the exception of IIb-11 at 1800°F (982°C), each of the five alloys experienced ductility increases at all three test temperatures as a result of the rolling. These increases generally represented 30 to 40 percent improvements over ductility of the extruded material.

(3) Extruded Plus Rolled Material-Partial Solution Heat Treated

Tensile test results for the extruded plus rolled Task I alloys heat treated using the partial solution heat treatment are listed in

Tables 15, 16, 17, and 18. These tables represent data collected at room temperature, 1200°, 1400°, and 1800°F (649°, 760°, and 982°C), respectively. In addition, the data for the five best Task I alloys are depicted in Figures 18, 19, 20, and 21.

As expected, strength levels at room temperature, 1200° and 1400°F (649° and 760°C) were increased considerably as a result of the thermomechanical processing and partial solution heat treatment. For example, the room temperature ultimate tensile strength of IIb-7 was increased from 213,000 psi (1470 MN/m^2) using the full solution heat treatment to 298,000 psi (2060 MN/m^2) using the partial solution heat treatment—an increase of about 40 percent. In addition to the ultra-high room temperature strength exhibited by IIb-7, the alloy also displayed extremely high ultimate strength values at 1200° and 1400°F (649° and 760°C) of about 258,000 and 212,000 psi (1780 and 1460 MN/m^2), respectively. Corresponding yield strength values at room temperature, 1200° and 1400°F (649° and 760°C) were 250,000, 226,000, and 187,000 psi (1720, 1560, and 1290 MN/m^2). It should also be noted that these ultra-high strength levels were achieved with corresponding elongations ranging from eight to thirteen percent.

Although IIb-7 was the strongest of the Task I alloys, the other four promising Task I alloys also displayed excellent strength capabilities in the room temperature to 1400°F (760°C) range. However, as depicted in Figure 21, the strength capabilities of all the alloys were drastically reduced at 1800°F (982°C) where the alloys became "superplastic". As no tests were conducted between the 1400° and 1800°F (760° and 982°C) test temperatures, the exact temperature range where the significant loss in strength is experienced is unknown.

b. Stress Rupture Testing

(1) Extruded Material-Full Solution Heat Treated

The results of stress rupture tests conducted on each alloy in the extruded and full solution heat treated condition are listed in Tables 19 and 20. The tables represent the results for tests conducted at 1400°F/90,000 psi and 1800°F/25,000 psi (760°C/621 MN/m^2 and 982°C/172 MN/M^2), respectively. Also, stress rupture data for the five best Task I alloys are summarized in Figures 22 and 23.

With respect to the tests conducted at 1400°F (760°C), the alloys displaying the best rupture life included IIb-8 and IIb-11. Rupture life values for the two alloys were 433 and 361 hours, respectively. Alloys IIb-7 and IIb-17 displayed good rupture life values of 213 and 240 hours, respectively; while the rupture life exhibited by IIb-12 was the lowest of the five best alloys at 84 hours. Rupture ductility values were low for all five alloys and ranged from 0.4 to 2.7 percent.

Alloys IIb-11 and IIb-17 displayed the highest 1800°F (982°C) rupture life values of 63 and 73 hours, while values for IIb-7 and

IIb-12 were slightly lower at 49 and 43 hours. The lowest rupture life of the five best alloys at 1800°F (982°C) was exhibited by IIb-8 at 29 hours. In contrast to tensile ductility, stress rupture ductility values were generally higher at 1800°F (982°C) than at 1400°F (760°C).

(2) Extruded Plus Rolled Material-Full Solution Heat Treated

Stress rupture test results for extruded plus rolled material subjected to full solution heat treatment are listed in Tables 21 and 22. Test conditions were the same as those described above for extruded material. The effect of the rolling on stress rupture properties was similar to its effect on tensile properties. General increases in rupture life at 1400°F (760°C) were effected by the rolling, especially for IIb-12 where rupture life increased from 84 to 587 hours. Of the five more promising Task I alloys, only IIb-8 failed to experience an increase in rupture life at 1400°F (760°C) as a result of the rolling. However, the noted improvements in rupture life at 1400°F (760°C) were not experienced at 1800°F (982°C); in fact, three of the five alloys experienced decreased rupture life as a result of the rolling. In addition, rolling improved the stress rupture ductility of four of the five alloys at 1400°F (760°C), and three of the five at 1800°F (982°C).

(3) Extruded Plus Rolled Material-Partial Solution Heat Treated

The results of stress rupture tests conducted at 1200°F/175,000 psi and 1400°F/90,000 psi (649°C/1207 MN/m^2 and 760°C/621 MN/m^2) on extruded plus rolled material heat treated using the partial solution heat treatment are summarized in Tables 23 and 24. These data are also depicted in Figures 26 and 27 for the five best Task I alloys.

With respect to the 1200°F (649°C) tests, IIb-7 displayed the best rupture life of the five more promising alloys at 225 hours in combination with a rupture ductility of about seven percent. Considering the extremely high stress level of 175,000 psi (1207 MN/m^2) used for the 1200°F (649°C) tests, the remaining four alloys also displayed good rupture strength. Rupture life values were 146 hours for IIb-11, 95 hours for IIb-12, and 59 hours each for IIb-8 and IIb-17.

Although previously described 1400°F (760°C) tensile properties for partial solution heat treated material were very good, we note from Table 24 and Figure 27 that rupture life at 1400°F (760°C) experienced a severe decrease as compared to full solution heat treated material. Rupture life at 1400°F (760°C) ranged from 13 to 31 hours for the five partial solution heat treated alloys, while the values ranged from 271 to 587 hours when the alloys were heat treated using the full solution heat treatment. Thus, while tensile properties for partial solution heat treated alloys were maintained at least to 1400°F (760°C), stress rupture capabilities are severely reduced at 1400°F (760°C).

7. Thermal Stability Studies

a. Tensile Testing

The results of room temperature tensile tests conducted on Task I extruded and full solution heat treated material after 1500 hours exposure at 1600°F (871°C) are summarized in Table 25. The data for ultimate tensile strength was compared with data obtained for unexposed material to determine the effect of the exposure. As all of the compositions experienced a loss in strength after exposure, the percent loss of ultimate tensile strength was plotted versus N_V number to establish thermal stability limits for the IIb alloy system. The resultant chart is illustrated in Figure 28. Using a ten percent loss in ultimate tensile strength as the maximum allowable loss, compositions exhibiting an electron vacancy number of 2.22 or greater would be considered unstable. In addition, compositions displaying electron vacancy numbers between 2.18 and 2.22 may or may not exhibit instability; data scatter renders this range uncertain. It should be noted that although highly-alloyed IIb-15 did not experience a decrease in ultimate tensile strength greater than ten percent, the cause for this was related to the very low room temperature strength in the as-heat treated condition of about 70,000 psi (482 MN/m^2). Strength values for the other compositions were in the 180,000 to 220,000 psi (1240 to 1520 MN/m^2) range.

With respect to the effects of the exposure on the strength of the five best Task I alloys, IIb-7, IIb-8 and IIb-17 all experienced decreases in strength, although the decreases were within the ten percent allowable limit. However, both IIb-11 and IIb-12 experienced significant decreases in strength over the allowable ten percent.

While IIb-12 experienced a severe strength decrease, the decrease for IIb-11 was less drastic. It is noted that the N_V number for IIb-11 at 2.22 is directly on the borderline for thermal stability; and a slight modification of the original chemistry from 4.5 percent aluminum to 4.3 percent aluminum would lower the N_v number to 2.16, which should be within the thermal stability limits.

Although the general effect of the exposure on ductility was detrimental, alloys IIb-7, IIb-8, and IIb-17 all experienced increased ductility as a result of the exposure. Alloys IIb-11 and IIb-12 both experienced severe ductility decreases.

b. Structural Examinations

Optical and electron microscopy and electrolytic extraction and X-ray phase identification were employed to determine the structural effects of the 1500 hour exposure on each of the as-extruded alloys. These results were compared with the results presented previously under "Heat Treatment Evaluation - Structural Examinations".

Figures 29 and 30 exemplify the microstructures resulting from thermally stable IIb-7 and thermally unstable IIb-11, respectively. As heat treated microstructures for these two alloys were previously illustrated in Figures 9 and 10. A comparison of the structures characteristic of as-heat treated material and as-heat treated plus exposed material reveals several significant structural changes. As a result of the exposure, both alloys have experienced a coarsening of the gamma prime particles. Also, considerable gamma prime agglomeration occurred for both materials. The agglomeration was more severe for IIb-11, as illustrated in Figure 31. A comparison of the structure before and after the exposure indicates the gamma prime particles have agglomerated into "pools" as a result of the exposure; the "pools" appear to have formed along grain boundaries, especially at boundary triple points. In addition, while grain boundary carbide precipitation is evident in both exposed samples, IIb-11 has formed a needle-like phase, which is illustrated in Figures 30 and 31.

The results of the X-ray diffraction studies conducted on residues extracted from full solution treated plus exposed Task I extruded materials are summarized in Table 26. A comparison of these results with the results obtained on as-heat treated materials (summarized in Table 8) reveals the effects of the exposure on minor phases. For most of the alloys, the MC-type carbide appears to be decomposing during exposure, resulting in the formation of increased amounts of M_6C and/or $M_{23}C_6$-type carbides. Also, in some cases, varying amounts of a mu phase were formed. This phase was formed in IIb-11, IIb-12, IIb-15, and IIb-16.

8. Data Analysis

The data derived under Task I was prepared for computer analysis and evaluated according to the procedures outlined in Appendix A of this report. Briefly, the properties obtained on extruded plus rolled material plus the thermal stability guide shown in Figure 28 were used to formulate the two Task II alloys. The first alloy, IIb-H, was formulated based on optimum 1400°F/90,000 psi (760°C/621 MN/m^2) stress rupture life in the full solution heat treated condition. The second alloy, IIb-L, was derived based on optimum 1200°F (649°C) yield strength in the partial solution heat treated condition.

B. Task II - Alloy Improvement

1. Alloy Preparation

The melting and processing of the two Task II alloys proceeded normally. The alloy designations, heat numbers, and aim and actual chemical analyses for the two alloys are listed in Table 27. The double vacuum melted ingots were first extruded at the Air Force Materials Laboratory and then processed to one-half inch (0.013 m) diameter bar stock in the same manner as the Task I alloys. Both alloys were successfully processed; however, the workability of IIb-L during rolling was rated below average, as several bars experienced slight cracking.

2. Heat Treatment Evaluation

a. Determination of Optimum Temperatures

The results of the heat treatment studies conducted on IIb-H and IIb-L are summarized in Table 28. The full solution heat treatment developed for IIb-H consisted of a solution treatment at 2225°F (1219°C) for two hours followed by an intermediate aging treatment at 1650°F (899°C) for 16 hours and a final aging treatment at 1400°F (760°C) for 16 hours. As described for the Task I alloys, the treatment was chosen to yield a grain size of ASTM 5 to 6 with the desired degree of carbide and gamma prime precipitation.

The partial solution heat treatment developed for IIb-L was the same treatment used for the majority of the Task I alloys. The treatment consisted of a conditioning age at 1600°F (871°C) for 16 hours followed by increasing the temperature to 2000°F (1093°C) for one hour, then oil quenching. A final age at 1400°F for 16 hours was also employed.

b. Structural Examinations

Studies were conducted on full solution heat treated IIb-H and partial solution heat treated IIb-L in a similar manner as described for the Task I alloys. The results of the electron microscopy studies conducted on the Task II alloys are illustrated in Figures 32 and 33. The photographs show the microstructures to be quite similar to those developed in Task I for full and partial solution heat treated material. The full solution heat treated IIb-H illustrated in Figure 32 exhibits the very fine gamma prime matrix precipitate with an absence of any agglomeration or gamma prime pools. Carbides evident include both matrix MC-type in addition to rather heavy concentrations of the M_6C-type in the grain boundaries. The partial solution heat treated structure for IIb-L resembles the structure achieved for the Task I alloys (see Figure 11). However, one variation appears to be the grain configuration. While the grains of IIb-7 were extremely fine and almost unresolvable at 5000X, the grains for IIb-L are easily resolvable at 5000X.

The results of the X-ray diffraction studies of extracted residues for as-heat treated IIb-H and IIb-L are summarized in Table 29. The MC-type carbide was the major phase for IIb-H, as was the case for the Task I alloys. In addition, a moderate amount of M_6C-type carbide was detected, accounting for the heavy grain boundary carbide viewed in the electron micrographs of Figure 32. IIb-L also contianed the MC-type carbide, but only in a moderate amount. The major phase present in IIb-L was an M_6C-type carbide.

3. Mechanical Testing

a. Tensile Testing

The notched and smooth tensile test results for IIb-H and IIb-L are summarized in Tables 30 and 31. Although IIb-H displayed good strength capabilities in conjunction with adequate ductility, strength values were not as high as those predicted in the computer analysis. In addition, while the strength values for IIb-H were better than those achieved by IIb-11 (the best full solution heat treated Task I alloy) at room temperature and 1400°F (760°C), the strength properties of IIb-11 were superior at 1800°F (982°C).

The strength levels displayed by IIb-L were also lower than the computer-predicted levels. However, while ultimate tensile strength and ductility at room temperature and 1200°F (649°C) were generally higher for IIb-7 (the best partial solution heat treated Task I alloy), yield strength values for IIb-L were slightly improved over those displayed by IIb-7. At 1400°F (760°C), ultimate and yield strength values for IIb-L were slightly improved over those exhibited by IIb-7.

With respect to the notch tensile tests, only IIb-L tested at 1200°F (649°C) appears to be notch sensitive (i.e., the notch strength was lower than the smooth tensile strength at that temperature). This tendency towards notch sensitivity is not displayed by IIb-L at either room temperature or 1400°F (760°C); and is not displayed by IIb-H at room temperature, 1400°, or 1800°F (760° or 982°C).

b. Stress Rupture Testing

The results of the stress rupture tests conducted on IIb-H and IIb-L are summarized in Tables 32 and 33, respectively. Rupture life values for both IIb-H and IIb-L fell well short of the computer-predicted values. In addition, these values were considerably less than those obtained for IIb-7 and IIb-11, the two best Task I alloys.

c. Creep Rupture Testing

The results of the creep rupture tests conducted on IIb-H and IIb-L are also listed in Tables 32 and 33. The time to 0.2% creep for IIb-H at 1400°F/90,000 psi (760°C/760 MN/m^2) was 34.5 hours. The results of the tests run at 1000°F/160,000 psi (538°C/1103 MN/m^2) for IIb-L were discontinued after 1000 hours as no measurable creep had occurred to that time.

4. Thermal Stability Studies

a. Tensile Testing

The results of the room temperature tensile tests conducted for IIb-H and IIb-L after 1500 hours exposure at 1600° and 1300°F (871°C and 704°C), respectively, are summarized in Table 34. The effects of the exposure on room temperature tensile properties varied considerably for each alloy. For example, while IIb-H experienced significant losses in ultimate and yield strengths up to about 20 percent, IIb-L experienced slight increases in both ultimate and yield strengths. Ductility values for both IIb-H and IIb-L were decreased as a result of the exposure.

b. Structural Examinations

Electron micrographs in Figures 34 and 35 typify the structures characteristic of exposed IIb-H and IIb-L, respectively. A comparison of these micrographs with those of Figures 32 and 33 indicate changes similar to those observed for the Task I alloys as a result of the exposure. The gamma prime particles in the IIb-H microstructure were coarsened considerably as a result of the exposure. In addition, IIb-H experienced heavy grain boundary carbide precipitation during the exposure. No significant microstructural changes were evident for IIb-L as a result of the exposure.

The results of the X-ray diffraction studies conducted on residues extracted from exposed IIb-H and IIb-L are summarized in Table 29. The effect of the exposure on IIb-H was a decomposition of the MC-type carbide and resultant excessive M_6C-type carbide precipitation. The degree of M_6C-type carbide precipitation was considerably greater for IIb-H than for any of the Task I alloys. The concentration of the MC-type carbide remained the same after exposure for IIb-L; however, the M_6C-type carbides were decomposed and resulted in the formation of moderate amounts of $M_{23}C_6$-type carbides and the same mu phase detected for some of the Task I alloys.

VI. SUMMARY OF RESULTS

The objective of this program was to optimize the chemical composition of NASA IIb for the purpose of developing advanced wrought nickel-base alloys for use in advanced gas turbine engines. The program was divided into two tasks. Task I consisted of a statistical analysis to determine the effects of five key elements (carbon, tungsten, tantalum, aluminum and hafnium) on resultant properties. Two compositions were formulated for Task II study based on the results of the Task I statistical analysis. The results of the program can be summarized as follows:

1. All Task I and II alloys were fabricable by extrusion and subsequent rolling.

2. Materials subjected to a full solution heat treatment displayed good overall properties, with outstanding 1400° to 1800°F (760° to 982°C) rupture strength. In contrast, materials subjected to a partial solution heat treatment displayed much higher tensile strengths up to 1400°F (760°C) and rupture strengths up to 1200°F (649°C), although tensile and rupture strength capabilities at higher temperatures were poor due to superplasticity.

3. The general effect of a low temperature [i.e., 2025°F (1107°C)] rolling after extrusion at 2100°F (1149°C) was to effect slight strength increases and significant ductility increases for full solution heat treated material. The effect of the rolling on partial solution heat treated material was not directly determined; however, it is well known that the increases in strength achieved are the result of this working/heat treating combination.

4. General thermal stability limits were established for the IIb alloy system. These limits indicate compositions with an N_v number greater than 2.22 will be unstable. To insure stability within the system, compositions should have N_v numbers below 2.18; the range between 2.18 and 2.22 is uncertain.

5. Of the seventeen Task I alloys, IIb-7 displayed the best properties in the partial solution heat treated condition. The alloy achieved ultimate tensile and yield strength values of 258,000 and 226,000 psi (1780 and 1560 MN/m^2) at 1200°F (649°C). The stress rupture life of IIb-7 at 1200°F and 175,000 psi (649°C and 1207 MN/m^2) was 250 hours.

6. Of the seventeen Task I alloys, IIb-11 displayed the best properties in the full solution heat treated condition. At

1400°F (760°C) the alloy displayed ultimate tensile and yield strength values of 185,000 and 157,000 psi (1275 and 1080 MN/m^2). The stress rupture life of IIb-11 at 1400°F and 90,000 psi (760°C and 621 MN/m^2) was 510 hours. Although the composition was found to be unstable after 1500 hours exposure at 1600°F (871°C), indications are that the instability can be eliminated with only a minor chemistry modification.

7. The Task I results were subjected to computer analysis and two alloys were formulated based on maximum strength with adequate ductility at 1200° and 1400°F (649° and 760°C). The computer analysis indicated a tendency towards slightly lower carbon and low hafnium for compositions designed for full or partial solution heat treatment applications. In addition, increased tungsten was predicted to be beneficial to alloy compositions designed for either high or low temperature properties. The results also indicated that increased tantalum would enhance low temperature properties, while increased aluminum would enhance high temperature properties. However, the overall properties displayed by the two Task II alloys formulated based on computer results were not as good as those obtained for the two Task I alloys, IIb-7 and IIb-11.

VII. CONCLUDING REMARKS

The exceptional strength characteristics of NASA IIb-7 at low operating temperatures in combination with adequate ductility render this alloy a strong candidate for future use in advanced turbine engines. As a result, it is recommended that a program be initiated to melt this alloy in production-sized heats, fabricate to disc configurations and evaluate the resultant product to determine the feasibility for producing the alloy on a production scale.

Although NASA IIb-11 displays excellent high temperature property capabilities, the alloy was found to be unstable. However, indications are that only slight chemistry modifications should be required to shift the composition within stability limits. As a result, additional chemistry studies are recommended using NASA IIb-11 as a base, to eliminate thermal instability and to further enhance the strength capabilities of the alloy.

REFERENCES

1. Collins, H. E., "Development of High Temperature Nickel-Base Alloys for Jet Engine Turbine Bucket Applications", NASA CR-72011, TRW, Inc., June, 1967.

2. Kent, W. B., "Wrought Nickel-Base Superalloys", NASA CR-72687, Universal-Cyclops Specialty Steel Division, Cyclops Corporation, March, 1970.

3. Woodyatt, L. R., C. T. Sims and H. J. Beattie, Jr., "Prediction of Sigma-Type Phase Occurance From Compositions in Austenitic Superalloys", Transactions AIME, 236 (April, 1966), 519 - 527.

TABLE 1

Modifications to the Original Base Composition of NASA IIb

	Chemical Composition (weight percent) for:													
	C	Cr	Co	Mo	W	Ta	Al	Ti	Hf	V	B	Zr	Ni	Nv
NASA IIb (original)	0.13	10.0	10.0	2.0	5.5	8.0	4.5	1.0	1.0	1.0	0.02	0.10	Bal.	2.47
NASA IIb (modified)	0.13	9.0	9.0	2.0	5.5	8.0	4.5	0.75	1.0	0.50	0.02	0.10	Bal.	2.18

TABLE 2

Summary of Constant and Variable Element Evaluation Levels For Seventeen Compositions in Statistical Design

Alloy	CONSTANT ELEMENTS Chemical Composition (weight percent) for:								VARIABLE ELEMENTS Chemical Composition (weight %) for:				
Designation	Cr	Co	Mo	Ti	V	B	Zr	Ni	C	W	Ta	Al	Hf
IIb-1	9.0	9.0	2.0	0.75	0.50	0.02	0.10	Balance	0.13	4.5	7.0	3.5	1.00
IIb-2	9.0	9.0	2.0	0.75	0.50	0.02	0.10	Balance	0.25	4.5	7.0	3.5	2.50
IIb-3	9.0	9.0	2.0	0.75	0.50	0.02	0.10	Balance	0.13	7.5	7.0	3.5	2.50
IIb-4	9.0	9.0	2.0	0.75	0.50	0.02	0.10	Balance	0.25	7.5	7.0	3.5	1.00
IIb-5	9.0	9.0	2.0	0.75	0.50	0.02	0.10	Balance	0.13	4.5	10.0	3.5	2.50
IIb-6	9.0	9.0	2.0	0.75	0.50	0.02	0.10	Balance	0.25	4.5	10.0	3.5	1.00
IIb-7	9.0	9.0	2.0	0.75	0.50	0.02	0.10	Balance	0.13	7.5	10.0	3.5	1.00
IIb-8	9.0	9.0	2.0	0.75	0.50	0.02	0.10	Balance	0.25	7.5	10.0	3.5	2.50
IIb-9	9.0	9.0	2.0	0.75	0.50	0.02	0.10	Balance	0.13	4.5	7.0	4.5	2.50
IIb-10	9.0	9.0	2.0	0.75	0.50	0.02	0.10	Balance	0.25	4.5	7.0	4.5	1.00
IIb-11	9.0	9.0	2.0	0.75	0.50	0.02	0.10	Balance	0.13	7.5	7.0	4.5	1.00
IIb-12	9.0	9.0	2.0	0.75	0.50	0.02	0.10	Balance	0.25	7.5	7.0	4.5	2.50
IIb-13	9.0	9.0	2.0	0.75	0.50	0.02	0.10	Balance	0.13	4.5	10.0	4.5	1.00
IIb-14	9.0	9.0	2.0	0.75	0.50	0.02	0.10	Balance	0.25	4.5	10.0	4.5	2.50
IIb-15	9.0	9.0	2.0	0.75	0.50	0.02	0.10	Balance	0.13	7.5	10.0	4.5	2.50
IIb-16	9.0	9.0	2.0	0.75	0.50	0.02	0.10	Balance	0.25	7.5	10.0	4.5	1.00
IIb-17	9.0	9.0	2.0	0.75	0.50	0.02	0.10	Balance	0.19	6.0	8.5	4.0	1.75

TABLE 3

Chemical Analyses of Seventeen Task I Heats

Alloy Designation	Heat Numbers	Chemical Composition (weight percent) for:												
		C	Cr	Co	Mo	W	Ta	Al	Ti	B	Zr	V	Hf	Ni
IIb-1 (Aim)		0.13	9.00	9.00	2.00	4.50	7.00	3.50	0.75	0.02	0.10	0.50	1.00	Bal
(KB2476)	KC1710 & 1711	0.12	8.95	9.02	1.90	4.65	6.96	3.53	0.74	0.02	0.11	0.49	0.97	Bal
IIb-2 (Aim)		0.25	9.00	9.00	2.00	4.50	7.00	3.50	0.75	0.02	0.10	0.50	2.50	Bal
(KB2505)	KC1746 & 1747	0.27	9.18	9.10	1.95	4.40	7.05	3.49	0.71	0.01	0.11	0.45	2.26	Bal
IIb-3 (Aim)		0.13	9.00	9.00	2.00	7.50	7.00	3.50	0.75	0.02	0.10	0.50	2.50	Bal
(KB2482)	KC1716 & 1717	0.12	8.75	9.05	1.89	7.55	7.28	3.50	0.74	0.01	0.10	0.46	2.48	Bal
IIb-4 (Aim)		0.25	9.00	9.00	2.00	7.50	7.00	3.50	0.75	0.02	0.10	0.50	1.00	Bal
(KB2483)	KC1718 & 1719	0.25	9.02	8.99	1.89	7.51	7.02	3.36	0.69	0.01	0.09	0.45	0.92	Bal
IIb-5 (Aim)		0.13	9.00	9.00	2.00	4.50	10.00	3.50	0.75	0.02	0.10	0.50	2.50	Bal
(KB2484)	KC1720 & 1721	0.13	8.90	9.05	1.86	4.55	10.02	3.46	0.72	0.01	0.10	0.46	2.42	Bal
IIb-6 (Aim)		0.25	9.00	9.00	2.00	4.50	10.00	3.50	0.75	0.02	0.10	0.50	1.00	Bal
(KB2485)	KC1722 & 1723	0.26	9.02	9.10	1.90	4.65	10.25	3.50	0.74	0.01	0.09	0.48	1.03	Bal
IIb-7 (Aim)		0.13	9.00	9.00	2.00	7.50	10.00	3.50	0.75	0.02	0.10	0.50	1.00	Bal
(KB2486)	KC1724 & 1725	0.12	8.75	9.01	1.84	7.65	9.98	3.34	0.70	0.01	0.09	0.45	0.95	Bal
IIb-8 (Aim)		0.25	9.00	9.00	2.00	7.50	10.00	3.50	0.75	0.02	0.10	0.50	2.50	Bal
(KB2487)	KC1726 & 1727	0.23	8.94	8.95	1.83	7.67	10.03	3.43	0.67	0.01	0.10	0.45	2.48	Bal
IIb-9 (Aim)		0.13	9.00	9.00	2.00	4.50	7.00	4.50	0.75	0.02	0.10	0.50	2.50	Bal
(KB2488)	KC1728 & 1729	0.12	8.92	9.30	1.93	4.57	7.04	4.52	0.76	0.01	0.10	0.49	2.46	Bal
IIb-10 (Aim)		0.25	9.00	9.00	2.00	4.50	7.00	4.50	0.75	0.02	0.10	0.50	1.00	Bal
(KB2506)	KC1748 & 1749	0.27	9.12	9.27	1.91	4.60	6.91	4.39	0.71	0.01	0.10	0.48	0.97	Bal

TABLE 3 (continued)

Chemical Analyses of Seventeen Task I Heats

Alloy Designation	Heat Numbers	Chemical Composition (weight percent) for: C	Cr	Co	Mo	W	Ta	Al	Ti	B	Zr	V	Hf	Ni
IIb-11 (Aim)		0.13	9.00	9.00	2.00	7.50	7.00	4.50	0.75	0.02	0.10	0.50	1.00	Bal
(KB2495)	KC1732 & 1733	0.12	8.82	9.09	1.94	7.65	7.01	4.51	0.76	0.01	0.09	0.48	1.00	Bal
IIb-12 (Aim)		0.25	9.00	9.00	2.00	7.50	7.00	4.50	0.75	0.02	0.10	0.50	2.50	Bal
(KB2496)	KC1734 & 1735	0.24	8.78	9.08	1.90	7.67	7.24	4.55	0.74	0.01	0.10	0.48	2.52	Bal
IIb-13 (Aim)		0.13	9.00	9.00	2.00	4.50	10.00	4.50	0.75	0.02	0.10	0.50	1.00	Bal
(KB2497)	KC1736 & 1737	0.13	8.91	9.10	1.94	4.60	10.02	4.51	0.77	0.01	0.08	0.48	1.00	Bal
IIb-14 (Aim)		0.25	9.00	9.00	2.00	4.50	10.00	4.50	0.75	0.02	0.10	0.50	2.50	Bal
(KB2498)	KC1738 & 1739	0.23	8.85	9.01	1.87	4.61	10.25	4.54	0.73	0.01	0.09	0.47	2.46	Bal
IIb-15 (Aim)		0.13	9.00	9.00	2.00	7.50	10.00	4.50	0.75	0.02	0.10	0.50	2.50	Bal
(KB2499)	KC1740 & 1741	0.13	8.80	8.97	1.87	7.58	10.27	4.50	0.72	0.01	0.09	0.47	2.43	Bal
IIb-16 (Aim)		0.25	9.00	9.00	2.00	7.50	10.00	4.50	0.75	0.02	0.10	0.50	1.00	Bal
(KB2500)	KC1742 & 1743	0.22	9.02	9.05	1.85	7.53	9.98	4.58	0.72	0.01	0.08	0.47	0.95	Bal
IIb-17 (Aim)		0.19	9.00	9.00	2.00	6.00	8.50	4.00	0.75	0.02	0.10	0.50	1.75	Bal
(KB2501)	KC1744 & 1745	0.18	8.93	9.00	1.84	6.20	8.58	4.04	0.72	0.01	0.09	0.48	1.71	Bal

TABLE 4

Gleeble Inherent Ductility Profiles For As-Cast Task I Alloys

Alloy Designation	Test Temperature (°F)	(°C)	Ultimate Strength (psi)	(MN/m^2)	Reduction Of Area (%)
IIb-1	2000	1093	44,300	306	14.5
	2050	1121	42,800	295	5.1
	2100	1149	24,400	168	3.6
	2150	1177	19,300	133	0
IIb-2	1950	1066	82,500	569	13.0
	2000	1093	66,000	455	14.2
	2050	1121	23,400	161	2.4
	2100	1149	20,900	144	0
IIb-3	1850	1010	100,000	690	12.5
	1900	1038	100,000	690	13.6
	1950	1066	62,500	431	8.3
	2000	1093	70,700	488	8.3
	2050	1121	34,000	234	4.8
	2100	1149	21,000	145	2.4
IIb-4	1900	1038	90,000	620	12.6
	2000	1093	38,200	263	10.6
	2050	1121	30,900	213	4.8
	2100	1149	28,100	194	3.9
IIb-5	1900	1038	113,000	780	11.6
	1950	1066	97,500	672	6.6
	2000	1093	73,800	508	2.1
	2100	1149	29,700	205	2.0
IIb-6	1850	1010	92,800	640	16.9
	1900	1038	92,000	634	10.0
	2000	1093	72,200	498	12.2
	2050	1121	54,700	377	21.8
	2100	1149	28,400	196	2.8
	2150	1177	18,200	126	0
IIb-7	2000	1093	86,000	593	15.4
	2050	1121	73,000	503	15.0
	2100	1149	65,000	448	5.4
	2150	1177	25,000	172	2.0
IIb-8	1900	1038	93,500	645	11.7
	2000	1093	73,700	508	11.3
	2050	1121	60,000	414	4.6
	2100	1149	27,900	192	3.1

TABLE 4 (continued)

Gleeble Inherent Ductility Profiles For As-Cast Task I Alloys

Alloy Designation	Test Temperature (°F)	Test Temperature (°C)	Ultimate Strength (psi)	Ultimate Strength (MN/m^2)	Reduction Of Area (%)
IIb-9	1900	1038	109,500	755	10.4
	1950	1066	83,200	574	5.1
	2000	1093	65,500	452	2.8
	2100	1149	27,600	190	3.1
IIb-10	1900	1038	88,700	612	14.6
	2000	1093	69,000	476	14.8
	2050	1121	50,300	347	2.4
	2100	1149	54,800	378	4.3
IIb-11	1900	1038	119,500	825	9.0
	2000	1093	95,000	655	11.8
	2050	1121	80,200	552	11.0
	2100	1149	62,500	431	3.5
IIb-12	1900	1038	107,000	738	9.4
	1950	1066	89,000	614	3.5
	2000	1093	72,000	496	6.8
	2100	1149	39,900	275	3.1
IIb-13	1900	1038	119,000	820	12.5
	1950	1066	98,500	679	8.3
	2000	1093	88,800	612	4.4
	2100	1149	21.700	150	0
IIb-14	1900	1038	113,000	780	6.3
	2000	1093	84,000	579	7.8
	2050	1121	73,200	504	4.0
	2100	1149	41,400	285	2.3
IIb-15	1900	1038	115,500	792	3.1
	2000	1093	89,500	617	5.3
	2050	1121	70,200	484	2.8
	2100	1149	17,500	121	0
IIb-16	1900	1038	112,000	772	4.4
	2000	1093	82,000	565	4.6
	2050	1121	26,700	184	1.6
	2100	1149	19,700	136	0
IIb-17	1900	1038	108,000	745	11.8
	2000	1093	70,300	485	10.4
	2050	1121	70,800	489	12.5
	2100	1149	26,000	179	1.6

Conditions: Heat to indicated test temperature, hold five minutes and test at a nominal strain rate of 5 $seconds^{-1}$.

TABLE 5

Optimum Full Solution Heat Treatments For Task I Extruded Plus Rolled Material

Composition Number	Selected Heat Treatment*
IIb-1	2250°F/2 hrs/RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC 1232°C/2 hrs /RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-2	2250°F/2 hrs /RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC 1232°C/2 hrs /RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-3	2225°F/2 hrs /RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC 1219°C/2 hrs /RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-4	2250°F/4 hrs /RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC 1232°C/4 hrs /RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-5	2250°F/2 hrs /RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC 1232°C/2 hrs /RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-6	2250°F/4 hrs /RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC 1232°C/4 hrs /RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-7	2250°F/2 hrs /RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC 1232°C/2 hrs /RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-8	2250°F/4 hrs /RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC 1232°C/4 hrs /RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-9	2250°F/4 hrs /RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC 1232°C/4 hrs /RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-10	2250°F/4 hrs /RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC 1232°C/4 hrs /RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-11	2250°F/2 hrs /RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC 1232°C/2 hrs /RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-12	2250°F/2 hrs /RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC 1232°C/2 hrs /RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-13	2250°F/4 hrs /RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC 1232°C/4 hrs /RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-14	2250°F/4 hrs /RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC 1232°C/4 hrs /RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-15	2250°F/2 hrs /RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC 1232°C/2 hrs /RAC + 871°C 16 hrs/RAC + 760°C/16 hrs/AC
IIb-16	2250°F/4 hrs /RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC 1232°F/4 hrs /RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-17	2250°F /2 hrs/ RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC 1232°C/2 hrs/ RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC

*RAC indicates Rapid Air Cool and AC, Air Cool.

TABLE 6

Optimum Full Solution Heat Treatments For
Task I Extruded Material

Composition Number	Selected Heat Treatment*
IIb-1	2225°F/2 hrs/RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC
	1219°C/2 hrs/RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-2	2225°F/2 hrs/RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC
	1219°C/2 hrs/RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-3	2225°F/2 hrs/RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC
	1219°C/2 hrs/RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-4	2225°F/2 hrs/RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC
	1219°C/2 hrs/RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-5	2250°F/2 hrs/RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC
	1232°C/2 hrs/RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-6	2225°F/2 hrs/RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC
	1219°C/2 hrs/RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-7	2225°F/2 hrs/RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC
	1219°C/2 hrs/RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-8	2225°F/2 hrs/RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC
	1219°C/2 hrs/RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-9	2250°F/2 hrs/RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC
	1232°C/2 hrs/RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-10	2225°F/2 hrs/RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC
	1219°C/2 hrs/RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-11	2225°F/2 hrs/RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC
	1219°C/2 hrs/RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-12	2225°F/2 hrs/RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC
	1219°C/2 hrs/RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-13	2250°F/2 hrs/RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC
	1232°C/2 hrs/RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-14	2250°F/2 hrs/RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC
	1232°C/2 hrs/RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-15	2225°F/2 hrs/RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC
	1219°C/2 hrs/RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-16	2250°F/2 hrs/RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC
	1232°C/2 hrs/RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC
IIb-17	2225°F/2 hrs/RAC + 1600°F/16 hrs/RAC + 1400°F/16 hrs/AC
	1219°C/2 hrs/RAC + 871°C/16 hrs/RAC + 760°C/16 hrs/AC

*RAC indicates Rapid Air Cool and AC, Air Cool.

TABLE 7

Optimum Partial Solution Heat Treatments For Task I Extruded Plus Rolled Material

Composition Number	Selected Heat Treatment*
IIb-1	1600°F/16 hrs + increase to 2000°F/1 hr/OQ + 1400°F/16 hrs/AC 871°C/16 hrs + increase to 1093°C/1 hr/OQ + 760°C/16 hrs/AC
IIb-2	1600°F/16 hrs + increase to 2000°F/1 hr/OQ + 1400°F/16 hrs/AC 871°C/16 hrs + increase to 1093°C/1 hr/OQ + 760°C/16 hrs/AC
IIb-3	1600°F/16 hrs + increase to 2000°F/1 hr/OQ + 1400°F/16 hrs/AC 871°C/16 hrs + increase to 1093°C/1 hr/OQ + 760°C/16 hrs/AC
IIb-4	1600°F/16 hrs + increase to 1950°F/1 hr/OQ + 1400°F/16 hrs/AC 871°C/16 hrs + increase to 1066°C/1 hr/OQ + 760°C/16 hrs/AC
IIb-5	1600°F/16 hrs + increase to 2000°F/1 hr/OQ + 1400°F/16 hrs/AC 871°C/16 hrs + increase to 1093°C/1 hr/OQ + 760°C/16 hrs/AC
IIb-6	1600°F/16 hrs + increase to 2000°F/1 hr/OQ + 1400°F/16 hrs/AC 871°C/16 hrs + increase to 1093°C/1 hr/OQ + 760°C/16 hrs/AC
IIb-7	1600°F/16 hrs + increase to 2000°F/1 hr/OQ + 1400°F/16 hrs/AC 871°C/16 hrs + increase to 1093°C/1 hr/OQ + 760°C/16 hrs/AC
IIb-8	1600°F/16 hrs + increase to 2000°F/1 hr/OQ + 1400°F/16 hrs/AC 871°C/16 hrs + increase to 1093°C/1 hr/OQ + 760°C/16 hrs/AC
IIb-9	1600°F/16 hrs + increase to 2000°F/1 hr/OQ + 1400°F/16 hrs/AC 871°C/16 hrs + increase to 1093°C/1 hr/OQ + 760°C/16 hrs/AC
IIb-10	1600°F/16 hrs + increase to 2000°F/1 hr/OQ + 1400°F/16 hrs/AC 871°C/16 hrs + increase to 1093°C/1 hr/OQ + 760°C/16 hrs/AC
IIb-11	1600°F/16 hrs + increase to 2000°F/1 hr/OQ + 1400°F/16 hrs/AC 871°C/16 hrs + increase to 1093°C/1 hr/OQ + 760°C/16 hrs/AC
IIb-12	1600°F/16 hrs + increase to 2000°F/1 hr/OQ + 1400°F/16 hrs/AC 871°C/16 hrs + increase to 1093°C/1 hr/OQ + 760°C/16 hrs/AC
IIb-13	1600°F/16 hrs + increase to 2000°F/1 hr/OQ + 1400°F/16 hrs/AC 871°C/16 hrs + increase to 1093°C/1 hr/OQ + 760°C/16 hrs/AC
IIb-14	1600°F/16 hrs + increase to 2000°F/1 hr/OQ + 1400°F/16 hrs/AC 871°C/16 hrs + increase to 1093°C/1 hr/OQ + 760°C/16 hrs/AC
IIb-15	1600°F/16 hrs + increase to 2000°F/1 hr/OQ + 1400°F/16 hrs/AC 871°C/16 hrs + increase to 1093°C/1 hr/OQ + 760°C/16 hrs/AC
IIb-16	1600°F/16 hrs + increase to 2000°F/1 hr/OQ + 1400°F/16 hrs/AC 871°C/16 hrs + increase to 1093°C/1 hr/OQ + 760°C/16 hrs/AC
IIb-17	1600°F/16 hrs + increase to 2000°F/1 hr/OQ + 1400°F/16 hrs/AC 871°C/16 hrs + increase to 1093°C/1 hr/OQ + 760°C/16 hrs/AC

*RAC indicates Rapid Air Cool; AC, Air Cool; and OQ, Oil Quench.

TABLE 8

X-Ray Diffraction Studies of Residues Extracted From Task I Extruded Alloys After Full Solution Heat Treatment

Alloy Designation	Relative Concentration* of Phases Present			
	MC	M_6C	$M_{23}C_6$	Mu-Phase
IIb-1	VS			
IIb-2	VS**			
IIb-3	VS**			
IIb-4	VS**			
IIb-5	VS**			
IIb-6	VS**			
IIb-7	M***			
IIb-8	VS**			
IIb-9	VS**			
IIb-10	VS**			
IIb-11	S	W		
IIb-12	VS**	W		
IIb-13	VS		W	
IIb-14	VS**			
IIb-15	W			W
IIb-16	M			
IIb-17	VS**			

*S represents Strong; M, Moderate; W, Weak; and V, Very.
**Indicates two distinct MC-type carbides.
***Indicates three distinct MC-type carbides.

TABLE 9

Room Temperature Tensile Properties For Task I Extruded Material Subjected to a Full Solution Heat Treatment

Composition Number	Ultimate Tensile Strength (KSI)	Ultimate Tensile Strength (MN/m^2)	0.2% Yield Strength (KSI)	0.2% Yield Strength (MN/m^2)	Elongation (%)	Reduction Of Area (%)
IIb-1	215.7	1487	147.7	1018	13.3	14.1
	216.9	1496	152.0	1048	12.0	15.3
IIb-2	211.6	1459	163.8	1129	10.0	11.9
	207.3	1429	155.4	1071	10.3	12.5
IIb-3	163.4	1127	161.4	1113	1.2	7.6
	184.3	1271	158.9	1096	3.7	5.9
IIb-4	213.6	1473	169.1	1166	12.2	15.1
	213.9	1475	173.5	1196	12.7	17.0
IIb-5	85.6**	590	-	-	-	-
	192.5	1327	154.9	1068	4.7	7.6
IIb-6	212.5	1465	171.6	1183	9.0	9.0
	212.9	1468	163.1	1125	9.6	10.2
IIb-7	201.4	1389	170.4	1175	5.0	7.1
	196.2	1353	173.8	1198	2.6	3.5
IIb-8	218.6	1507	176.3	1216	7.2	10.7
	224.5	1548	169.9	1171	9.4	9.8
IIb-9	153.9	1061	152.9	1054	0.7	3.4
	165.9	1144	144.6	997	3.0	4.6
IIb-10	190.6	1314	160.9	1109	7.9	9.8
	204.2	1408	161.5	1114	10.7	13.6
IIb-11	202.9	1399	170.8	1178	8.5	10.4
	211.0	1455	170.8	1178	10.0	11.2
IIb-12	126.8**	874	126.8	874	0.4	1.0
	207.5	1431	179.3	1236	8.1	10.9
IIb-13	177.4	1223	171.7	1184	1.8	5.2
	154.2	1063	154.2	1063	1.4	1.5
IIb-14	138.3	954	138.3	954	0.6	3.1
	81.7**	563	81.7	563	0.8	1.0
IIb-15	60.1	414	60.1	414	0.9	0.6
	78.4	541	78.4	541	0.6	0.9
IIb-16	155.1	1069	155.1	1069	0.6	0.0
	186.0	1282	182.0	1255	1.0	1.2
IIb-17	153.7**	1060	153.7	1060	1.2	1.3
	181.9	1254	168.1	1159	3.1	7.5

** Defective Specimen.

TABLE 10

1400°F (760°C) Tensile Properties For Task I Extruded Material Subjected to A Full Solution Heat Treatment

Composition Number	Ultimate Tensile Strength (KSI)	Ultimate Tensile Strength (MN/m^2)	0.2% Yield Strength (KSI)	0.2% Yield Strength (MN/m^2)	Elongation (%)	Reduction Of Area (%)
IIb-1	168.6	1162	135.4	934	9.4	15.4
	169.0	1165	143.6	990	8.7	11.3
IIb-2	163.5	1127	141.1	973	3.4	7.4
	168.0	1158	142.9	985	4.2	9.8
IIb-3	163.3	1126	143.6	990	1.9	5.8
	175.1	1207	149.1	1028	2.8	6.8
IIb-4	154.4*	1065	144.3	995	1.2	3.9
	157.8	1088	147.8	1019	2.4	3.8
IIb-5	170.3	1174	139.2	960	1.3	0.5
	149.4	1030	136.8	943	0.9	4.5
IIb-6	172.5	1189	148.1	1021	4.3	5.3
	172.1	1187	147.1	1014	3.8	3.2
IIb-7	177.6	1125	152.6	1052	1.9	8.4
	178.5	1231	154.6	1066	1.9	5.7
IIb-8	185.0	1276	154.9	1068	5.6	9.9
	186.1	1283	152.8	1054	5.4	8.3
IIb-9	137.9	951	136.4	940	0.4	4.0
	142.2	980	138.5	955	1.3	1.5
IIb-10	167.2	1153	145.2	1001	6.2	5.4
	165.1	1138	148.0	1020	6.0	9.1
IIb-11	180.5	1245	150.7	1039	8.6	13.5
	178.5**	1231	155.2	1070	3.0	5.4
IIb-12	178.3	1229	158.1	1090	5.1	7.3
	72.1**	497	72.1	497	0.6	1.0
IIb-13	176.6	1218	148.2	1022	2.7	5.9
	177.5	1224	148.9	1027	2.5	3.5
IIb-14	73.1**	504	73.1	504	1.0	3.0
	165.9	1144	146.5	1010	1.5	4.5
IIb-15	43.3	299	43.3	299	0.2	1.7
	72.8	502	72.8	502	0.6	0.1
IIb-16	149.4	1030	149.4	1030	0.4	0.5
	118.5	817	118.5	817	0.7	1.5
IIb-17	182.5	1258	152.3	1050	4.9	3.0
	181.5	1251	151.3	1043	6.4	10.5

*Specimen broke in shoulder.
**Defective Specimen.

TABLE 11

1800°F (982°C) Tensile Properties For Task I Extruded Material Subjected to A Full Solution Heat Treatment

Composition Number	Ultimate Tensile Strength		0.2% Yield Strength		Elongation (%)	Reduction Of Area (%)
	(KSI)	(MN/m^2)	(KSI)	(MN/m^2)		
IIb-1	59.8	412	53.7	370	3.9	6.1
	57.0	393	50.4	348	4.1	5.9
IIb-2	60.4	416	56.0	386	3.2	1.9
	57.4	396	51.0	352	3.4	5.9
IIb-3	69.5	479	59.1	407	2.5	1.9
	67.9	468	56.8	392	1.8	3.8
IIb-4	49.9	344	49.1	339	2.3	4.7
	51.5	355	51.3	354	1.6	2.2
IIb-5	56.1	387	53.7	370	1.2	2.5
	67.9	468	58.5	403	1.1	0.5
IIb-6	58.1	401	56.4	389	1.8	2.0
	61.9	427	56.7	391	1.6	1.9
IIb-7	76.6	528	65.6	452	1.5	4.2
	77.8	536	63.7	439	3.5	4.3
IIb-8	73.0	503	64.0	441	2.5	4.1
	71.1	490	58.7	405	3.1	1.5
IIb-9	50.3	347	50.3	347	0.2	0.5
	54.0	372	52.9	365	0.6	1.3
IIb-10	62.0	427	49.1	339	2.1	1.7
	60.5	417	49.0	338	2.9	2.4
IIb-11	74.5*	514	72.7	501	2.3	0.6
	85.5	590	71.2	491	3.5	4.2
IIb-12	20.3	140	20.3	140	0.5	2.5
	59.3	409	59.3	409	0.5	0.1
IIb-13	62.3	430	62.3	430	1.1	2.5
	39.8	274	39.8	274	0.8	0.8
IIb-14	66.1	456	64.6	445	1.6	0.9
	65.9	454	62.5	431	1.5	2.3
IIb-15	52.7	363	52.7	363	0.7	0.5
	21.7	150	21.7	150	0.5	2.4
IIb-16	58.1	401	58.1	401	0.2	0.9
	49.4	341	49.4	341	0.7	1.1
IIb-17	74.9	516	58.2	401	3.0	4.9
	70.7	487	61.5	424	1.8	5.3

*Specimen broke in shoulder.

TABLE 12

Room Temperature Tensile Properties For Task I Extruded Plus Rolled Material Subjected to a Full Solution Heat Treatment

Composition Number	Ultimate Tensile Strength (KSI)	Ultimate Tensile Strength (MN/m^2)	0.2% Yield Strength (KSI)	0.2% Yield Strength (MN/m^2)	Elongation (%)	Reduction Of Area (%)
IIb-1	218.3	1505	155.0	1069	13.2	17.7
	217.9	1502	158.3	1091	13.2	16.1
IIb-2	211.0	1455	157.2	1084	12.1	13.9
	212.7	1467	154.8	1067	12.8	16.5
IIb-3	201.1	1387	162.4	1120	6.5	9.7
	204.0	1407	160.3	1105	8.6	10.0
IIb-4	222.3	1533	169.6	1169	13.4	21.9
	226.3	1560	166.9	1151	13.5	21.9
IIb-5	210.4	1451	168.5	1162	11.1	11.7
	201.9	1392	160.6	1107	6.1	7.6
IIb-6	216.4	1492	168.3	1160	10.4	12.5
	168.0**	1158	167.5	1155	1.3	4.8
IIb-7	211.5	1458	167.6	1156	7.9	10.1
	215.4	1485	167.2	1153	8.5	8.5
IIb-8	216.8	1495	175.5	1210	8.0	10.9
	188.1**	1297	171.5	1182	2.1	4.2
IIb-9	181.4	1251	157.1	1083	5.5	9.0
	178.3	1229	158.5	1093	5.0	7.9
IIb-10	205.5	1417	160.8	1109	13.5	14.1
	207.1	1428	158.5	1093	14.6	16.7
IIb-11	213.5	1472	172.8	1191	10.1	14.3
	213.1	1469	173.4	1196	9.5	12.8
IIb-12	219.5	1513	176.4	1216	10.5	12.8
	217.3	1498	174.7	1205	10.7	13.2
IIb-13	212.5	1465	172.7	1191	9.1	8.8
	208.8	1440	167.5	1155	8.4	8.3
IIb-14	200.7	1384	171.3	1181	7.4	6.9
	212.4	1464	169.9	1171	9.6	13.7
IIb-15	92.9*	641	92.9	641	0.4	0.3
	80.6	556	80.6	556	0.9	0
IIb-16	199.1	1373	177.5	1224	5.0	8.4
	203.9	1406	181.7	1253	5.2	7.2
IIb-17	218.5	1507	167.4	1154	11.3	12.8
	218.6	1507	165.9	1144	11.6	13.0

*Specimen broke in shoulder.
**Defective Specimen.

TABLE 13

1400°F (760°C) Tensile Properties For Task I Extruded Plus Rolled Material Subjected to a Full Solution Heat Treatment

Composition Number	Ultimate Tensile Strength (KSI)	Ultimate Tensile Strength (MN/m^2)	0.2% Yield Strength (KSI)	0.2% Yield Strength (MN/m^2)	Elongation (%)	Reduction Of Area (%)
IIb-1	167.1	1152	134.8	929	6.6	12.0
	168.1	1159	139.4	961	6.8	8.2
IIb-2	166.5	1148	143.6	990	3.6	5.7
	164.7	1136	138.2	953	4.2	5.4
IIb-3	176.9	1220	148.7	1025	4.1	7.6
	173.9	1199	142.4	982	3.4	3.6
IIb-4	127.0*	876	127.0	876	1.0	2.4
	152.8	1054	146.0	1007	1.9	6.5
IIb-5	153.1	1056	139.8	964	1.6	3.7
	150.7	1039	141.0	972	1.4	1.4
IIb-6	176.8	1219	156.0	1076	2.8	3.8
	175.1	1207	161.9	1116	2.0	3.1
IIb-7	190.3	1312	148.6	1025	5.3	9.5
	183.2	1263	148.6	1025	4.2	12.6
IIb-8	178.6	1231	149.3	1029	4.7	10.1
	176.8	1219	147.6	1018	5.4	7.3
IIb-9	155.0	1069	143.0	986	1.4	4.7
	164.2	1132	141.6	976	1.9	4.1
IIb-10	143.1	987	142.1	980	1.4	0.9
	151.2	1043	144.0	993	1.5	3.6
IIb-11	183.3	1264	157.4	1085	11.7	13.5
	187.3	1291	156.9	1082	11.9	12.0
IIb-12	183.5	1265	166.5	1148	9.8	15.8
	186.3	1285	161.6	1114	7.4	9.1
IIb-13	183.5	1265	162.9	1123	8.0	11.5
	181.2	1249	150.1	1035	11.0	14.8
IIb-14	178.6	1231	153.8	1060	11.0	15.7
	164.6	1135	153.0	1055	2.4	5.1
IIb-15	102.0	703	102.0	703	0.4	0.1
	48.7	336	48.7	336	1.0	-
IIb-16	178.3	1229	171.9	1185	1.5	1.1
	187.7	1294	160.5	1107	4.2	10.3
IIb-17	179.3	1236	146.9	1013	8.7	10.6
	176.5	1217	150.1	1035	8.6	13.3

*Specimen broke in shoulder.

TABLE 14

1800°F (982°C) Tensile Properties For Task I Extruded Plus Rolled Material Subjected to a Full Solution Heat Treatment

Composition Number	Ultimate Tensile Strength (KSI)	Ultimate Tensile Strength (MN/m^2)	0.2% Yield Strength (KSI)	0.2% Yield Strength (MN/m^2)	Elongation (%)	Reduction Of Area (%)
IIb-1	61.7	425	50.8	350	3.2	3.8
	61.0	421	47.0	324	2.3	3.7
IIb-2	60.1	414	47.4	327	4.4	5.2
	60.7	419	49.4	341	4.1	3.9
IIb-3	68.9	475	56.9	392	3.0	3.1
	63.1	435	56.6	390	1.8	2.0
IIb-4	55.0	379	49.2	339	2.3	3.7
	47.7	329	47.0	324	1.0	1.5
IIb-5	42.3*	292	42.3	292	1.0	0.6
	67.5	465	52.7	363	3.1	6.0
IIb-6	47.2*	325	47.2	325	0.8	0.7
	58.1	401	57.7	398	1.1	0.6
IIb-7	74.4	513	65.6	452	4.1	3.1
	76.9	530	57.3	395	3.0	6.1
IIb-8	67.1	463	58.7	405	3.2	3.6
	71.6	494	64.1	442	3.3	5.0
IIb-9	50.8	350	50.8	350	0.7	0.6
	55.3	381	53.8	371	1.0	0.1
IIb-10	60.1	414	46.3	319	1.6	2.6
	54.9	379	42.8	295	2.3	1.0
IIb-11	74.4	513	71.2	491	1.3	3.6
	85.7	591	70.1	483	2.9	2.2
IIb-12	70.9	489	69.4	479	0.9	2.0
	83.1	573	66.6	459	2.1	3.2
IIb-13	65.9	454	62.0	427	1.3	2.3
	60.6	418	60.4	416	0.5	0.9
IIb-14	77.8	536	59.2	408	2.4	0.6
	73.4	506	61.8	426	1.8	1.5
IIb-15	32.3	223	32.3	223	0.4	0
	41.1	283	41.1	283	0.8	0
IIb-16	29.7	205	29.7	205	0.3	1.7
	48.5	334	48.5	334	0.1	0.5
IIb-17	76.6	528	59.1	407	4.4	5.3
	79.2	546	54.7	377	3.4	4.9

*Specimen broke in shoulder.

TABLE 15

Room Temperature Tensile Properties For Task I Extruded Plus Rolled Material Subjected to a Partial Solution Heat Treatment

Composition Number	Ultimate Tensile Strength (KSI)	Ultimate Tensile Strength (MN/m^2)	0.2% Yield Strength (KSI)	0.2% Yield Strength (MN/m^2)	Elongation (%)	Reduction of Area (%)
IIb-1	273.7	1887	209.4	1444	12.5	13.3
	269.4	1858	213.7	1473	10.9	15.3
IIb-2	247.7	1708	201.4	1389	10.3	14.4
	244.4	1685	199.7	1377	9.3	14.3
IIb-3	271.3	1871	219.3	1512	10.4	13.8
	264.6	1824	218.1	1504	10.5	13.4
IIb-4	265.6	1831	220.1	1518	9.7	12.6
	261.6	1804	214.7	1480	10.5	17.0
IIb-5	262.0	1806	215.4	1485	9.5	13.1
	266.8	1840	217.1	1497	9.8	12.7
IIb-6	261.9	1806	225.1	1552	8.4	11.0
	261.9	1806	225.9	1558	8.6	11.0
IIb-7	309.1	2131	250.4	1727	9.8	15.9
	286.9	1978	249.4	1720	8.3	9.5
IIb-8	255.7	1763	225.5	1555	5.8	7.8
	257.2	1773	227.1	1566	6.2	10.1
IIb-9	255.4	1761	208.1	1435	10.2	12.4
	248.4	1713	205.4	1416	10.4	13.7
IIb-10	243.2	1677	203.4	1402	9.8	13.9
	235.5	1624	193.5	1334	9.8	15.1
IIb-11	267.6	1845	225.5	1555	9.3	11.6
	264.4	1823	223.9	1544	9.3	14.7
IIb-12	244.8	1688	212.7	1467	7.6	7.9
	247.1	1704	211.3	1457	8.9	10.7
IIb-13	244.7	1687	211.4	1458	7.7	11.9
	226.3	1560	214.3	1478	4.8	7.8
IIb-14	244.2	1684	211.1	1456	8.1	9.4
	103.9**	716	103.9	716	0.8	2.7
IIb-15	241.3	1664	234.4	1616	2.1	4.0
	240.1	1655	231.6	1597	2.4	6.6
IIb-16	238.3	1643	221.0	1524	4.4	6.7
	245.2	1691	220.5	1520	5.6	8.0
IIb-17	256.1	1766	220.5	1520	8.9	11.2
	264.3	1822	220.7	1522	10.3	13.6

**Defective Specimen.

TABLE 16

1200°F (649°C) Tensile Properties For Task I Extruded Plus Rolled Material Subjected to a Partial Solution Heat Treatment

Composition Number	Ultimate Tensile Strength (KSI)	Ultimate Tensile Strength (MN/m^2)	0.2% Yield Strength (KSI)	0.2% Yield Strength (MN/m^2)	Elongation (%)	Reduction of Area (%)
IIb-1	229.7	1584	197.6	1362	5.1	5.8
IIb-2	203.6	1404	181.9	1254	4.3	9.4
IIb-3	231.5	1596	198.9	1371	7.5	8.4
IIb-4	241.1*	1662	208.6	1438	6.3	0.5
IIb-5	237.7	1639	204.4	1409	7.0	8.3
IIb-6	229.0	1579	206.6	1425	7.7	11.0
IIb-7	257.9	1778	225.6	1556	6.7	8.4
IIb-8	225.9	1558	201.7	1391	4.1	9.0
IIb-9	223.5	1541	195.7	1349	10.0	11.4
IIb-10	208.4	1437	184.5	1272	4.0	9.8
IIb-11	230.8	1591	209.2	1442	7.8	10.4
IIb-12	221.2	1525	200.5	1382	5.8	7.2
IIb-13	221.4	1527	201.4	1389	7.4	12.8
IIb-14	212.2	1463	199.4	1375	2.0	10.2
IIb-15	231.7	1598	212.5	1465	2.5	6.8
IIb-16	224.4	1547	209.1	1442	4.6	8.4
IIb-17	229.1	1580	203.0	1400	9.0	11.1

*Specimen broke in shoulder.

TABLE 17

1400°F (760°C) Tensile Properties For Task I Extruded Plus Rolled Material Subjected to a Partial Solution Heat Treatment

Composition Number	Ultimate Tensile Strength (KSI)	Ultimate Tensile Strength (MN/m^2)	0.2% Yield Strength (KSI)	0.2% Yield Strength (MN/m^2)	Elongation (%)	Reduction of Area (%)
IIb-1	191.6	1321	166.4	1147	3.7	7.0
	188.1*	1297	150.9	1040	2.3	0.5
IIb-2	189.3	1305	171.9	1185	3.9	5.2
	167.7*	1156	164.0	1131	1.2	1.5
IIb-3	159.7**	1101	159.7	1101	1.3	6.4
	200.2	1380	183.8	1267	3.8	9.9
IIb-4	160.6*	1107	160.6	1107	0.1	2.2
	152.2	1049	152.2	1049	1.0	0.8
IIb-5	198.2	1367	182.5	1258	4.2	6.5
	169.8*	1171	166.7	1149	1.1	0.9
IIb-6	168.1*	1159	160.6	1107	1.7	1.8
	191.3	1319	178.0	1227	5.9	10.8
IIb-7	190.9*	1316	186.6	1287	2.0	1.3
	211.8	1460	186.8	1288	4.0	9.0
IIb-8	201.2	1387	184.4	1271	2.1	3.4
	172.5**	1189	172.5	1189	1.0	2.0
IIb-9	193.9	1137	173.6	1197	5.7	7.8
	189.8	1309	148.0	1020	5.0	10.8
IIb-10	177.8	1226	166.7	1149	7.1	10.9
	183.3	1264	167.8	1157	5.2	11.3
IIb-11	196.7	1356	176.5	1217	4.4	4.9
	199.7	1377	180.5	1245	4.8	7.1
IIb-12	193.4	1333	169.4	1168	4.5	5.7
	195.7	1349	178.4	1230	4.5	5.6
IIb-13	145.0**	1000	143.0	986	1.3	1.2
	194.3	1340	174.6	1204	5.1	7.0
IIb-14	187.3	1291	173.2	1194	4.2	3.5
	174.8	1205	164.2	1132	1.7	2.2
IIb-15	165.7*	1143	164.2	1132	1.3	0.3
	192.8	1329	167.4	1154	3.4	2.5
IIb-16	189.9	1309	175.8	1212	3.4	7.5
	174.9	1206	169.9	1171	2.2	1.7
IIb-17	198.9	1371	184.9	1275	5.5	9.0
	198.9	1371	182.4	1258	6.0	9.3

*Specimen broke in shoulder.
**Defective Specimen.

TABLE 18

1800°F (982°C) Tensile Properties For Task I Extruded Plus Rolled Material Subjected to a Partial Solution Heat Treatment

Composition Number	Ultimate Tensile Strength (KSI)	Ultimate Tensile Strength (MN/m^2)	0.2% Yield Strength (KSI)	0.2% Yield Strength (MN/m^2)	Elongation (%)	Reduction of Area (%)
IIb-1	35.3	243	21.3	147	60.8	98.6
	38.5	265	24.1	166	66.5	97.6
IIb-2	32.8	226	15.9	110	62.2	87.9
	31.4	217	16.8	116	70.8	91.7
IIb-3	22.7	157	7.5	52	129.6	98.7
	24.4	168	8.4	58	139.0	98.7
IIb-4	34.3	236	21.1	145	46.6	76.4
	34.1	235	21.1	145	45.3	73.2
IIb-5	19.6**	135	10.5	72	8.5	15.7
	19.5	134	4.6	32	200.6	98.4
IIb-6	33.3	230	17.6	121	48.3	82.7
	32.4	223	13.3	92	50.5	81.2
IIb-7	31.1	214	18.3	126	101.4	98.3
	33.1	228	18.6	128	53.0	92.1
IIb-8	34.6	239	20.7	143	49.0	75.2
	37.9	261	21.9	151	72.3	79.2
IIb-9	21.0	145	7.8	54	131.0	98.1
IIb-10	30.8	212	15.5	107	64.7	88.6
IIb-11	29.0	200	10.9	75	66.3	94.9
IIb-12	22.6	156	8.7	60	101.1	92.5
IIb-13	19.7	136	5.0	34	202.3	98.7
IIb-14	16.4	113	2.9	20	115.2	93.6
IIb-15	19.1	132	7.8	54	240.7	98.4
IIb-16	20.5	141	8.6	49	124.3	94.3
IIb-17	25.9	179	12.0	83	109.1	98.0

**Defective Specimen.

TABLE 19

1400°F/90,000 psi (760°C/621 MN/m^2) Stress Rupture Properties for Task I Extruded Material Subjected to a Full Solution Heat Treatment

Composition Number	Rupture Life (hours)	Elongation (%)	Reduction Of Area (%)
IIb-1	126.0	2.0	2.5
	127.7	2.9	1.1
IIb-2	57.7	2.1	2.9
	49.8	2.2	1.4
IIb-3	56.0	0.7	3.3
	9.8**	-	-
IIb-4	15.8*	-	-
	26.8	0.8	3.9
IIb-5	14.2	1.3	3.1
	19.1	1.4	3.0
IIb-6	39.5*	2.3	0.3
	121.6	1.4	1.9
IIb-7	212.8	0.8	2.7
	129.5*	0.3	-
IIb-8	507.4	2.9	2.0
	359.1	2.0	1.0
IIb-9	8.3	1.0	0.4
	15.0	0.8	1.6
IIb-10	8.4*	-	-
	20.7*	-	-
IIb-11	347.0	3.3	2.2
	374.1	3.1	1.5
IIb-12	0.1**	0.9	0.4
	83.8	0.9	0.3
IIb-13	40.6	0.7	2.5
	65.0	0.7	2.0
IIb-14	0.2	0.9	3.2
	0.1**	0.7	0.4
IIb-15	0.1	0.5	0.1
	0.0*	-	-
IIb-16	2.1	0.9	0.2
	0.1	0.1	-
IIb-17	200.4	2.0	3.9
	280.4	1.4	1.3

*Specimen broke in shoulder.
**Defective Specimen.

TABLE 20

1800°F/25,000 psi (982°C/172 MN/m^2) Stress Rupture Properties for Task I Extruded Material Subjected to a Full Solution Heat Treatment

Composition Number	Rupture Life (hours)	Elongation (%)	Reduction Of Area (%)
IIb-1	20.9	9.3	7.5
	21.6	7.7	7.7
IIb-2	15.2	9.8	8.2
	12.6	7.6	7.2
IIb-3	24.7	6.0	7.2
	22.8	5.4	2.9
IIb-4	6.7	7.6	10.4
	5.3	8.1	9.7
IIb-5	7.1	1.9	0.5
	17.2	3.3	1.5
IIb-6	14.7	6.0	4.3
	14.8	6.5	5.9
IIb-7	50.1	3.8	2.7
	47.4	4.7	4.0
IIb-8	27.3	18.7	17.6
	30.7	14.6	12.5
IIb-9	2.8	1.7	0.7
	1.5	2.0	0.9
IIb-10	8.8	7.6	7.4
	11.0	8.1	7.4
IIb-11	70.3	6.3	6.1
	56.0	6.1	7.4
IIb-12	52.3	6.5	7.7
	33.3	2.4	1.1
IIb-13	35.4	2.4	4.4
	21.1	2.3	2.1
IIb-14	9.6	1.7	1.7
	19.2	4.0	5.0
IIb-15	3.2	2.1	1.8
	0.1	-	-
IIb-16	39.2	6.8	11.0
	0.6	0.3	-
IIb-17	30.5	4.9	6.2
	115.1	5.6	8.1

TABLE 21

1400°F/90,000 psi (760°C/621 MN/m^2) Stress Rupture Properties For Task I Extruded Plus Rolled Material Subjected to a Full Solution Heat Treatment

Composition Number	Rupture Life (hours)	Elongation (%)	Reduction Of Area (%)
IIb-1	44.8	4.4	2.8
	112.5	2.5	4.0
IIb-2	35.8*	0.6	-
	42.0	2.2	11.0
IIb-3	157.5	2.3	4.9
	89.0	0.5	3.7
IIb-4	9.6*	1.0	-
	20.4	0.9	4.7
IIb-5	60.7	1.8	3.6
	42.1	1.5	1.6
IIb-6	6.6*	-	-
	13.7*	-	-
IIb-7	198.0	0.7	0.8
	343.2	0.9	1.4
IIb-8	53.9*	-	-
	304.8	2.4	5.2
IIb-9	4.5	0.7	1.5
	2.2	0.8	3.3
IIb-10	2.6*	0.1	-
	12.5*	1.2	-
IIb-11	516.3	1.8	6.5
	506.4	2.5	2.0
IIb-12	587.9	3.9	5.2
	586.5	1.7	3.8
IIb-13	425.8	1.9	3.8
	308.6	3.1	4.3
IIb-14	44.0**	-	-
	474.1	3.3	5.3
IIb-15	6.6*	0.3	-
	1.4	1.1	-
IIb-16	26.8	1.0	0.2
	23.4*	0.5	-
IIb-17	172.6	3.3	3.9
	444.9	3.0	5.8

*Specimen broke in shoulder.
**Defective Specimen.

TABLE 22

1800°F/25,000 psi (982°C/172 MN/m^2) Stress Rupture Properties For Task I
Extruded Plus Rolled Material Subjected to a Full Solution Heat Treatment

Composition Number	Rupture Life (hours)	Elongation (%)	Reduction Of Area (%)
IIb-1	14.6	6.3	8.7
	10.6	9.1	12.9
IIb-2	9.1	9.7	11.9
	6.6	7.2	10.5
IIb-3	16.5	4.6	5.4
	0.1**	-	-
IIb-4	2.4	10.6	10.8
	3.2	6.6	12.3
IIb-5	16.7	3.7	6.5
	18.9	5.7	6.0
IIb-6	10.5	8.0	7.4
	12.5	8.6	7.4
IIb-7	37.3	5.5	5.1
	38.8	6.0	4.7
IIb-8	14.6	8.1	10.2
	12.1	8.4	11.3
IIb-9	7.0	1.7	1.0
	6.7	1.0	1.5
IIb-10	4.8	8.0	13.9
	4.7	6.9	10.1
IIb-11	64.2	6.1	7.3
	61.9	4.7	4.4
IIb-12	47.5	9.5	11.1
	48.9	8.5	12.1
IIb-13	33.3	3.5	5.7
	33.1	7.1	7.1
IIb-14	16.3	5.3	4.3
	27.9	7.0	8.8
IIb-15	7.2	2.2	0.4
	0.1	0.9	-
IIb-16	35.8	6.9	14.3
	40.0	10.8	20.6
IIb-17	31.6	7.0	10.4
	25.0*	0.2	-

*Specimen broke in shoulder.

**Defective Specimen.

TABLE 23

1200°F/175,000 psi (649°C/1207 MN/m^2) Stress Rupture Properties For Task I Extruded Plus Rolled Material Subjected to a Partial Solution Heat Treatment

Composition Number	Rupture Life (hours)	Elongation (%)	Reduction of Area (%)
IIb-1	145.5	4.0	9.0
	93.3	2.7	8.2
IIb-2	7.0	0.4	8.5
	8.0	0.7	8.5
IIb-3	425.9	4.2	8.7
	125.2	1.9	5.8
IIb-4	46.8	5.0	5.2
	72.4	1.9	5.8
IIb-5	396.6	2.5	12.9
	367.3	2.5	10.6
IIb-6	46.1	1.2	7.5
	68.1	3.5	11.8
IIb-7	165.2	4.5	6.0
	284.5	4.6	7.6
IIb-8	40.4*	1.7	-
	78.2*	-	-
IIb-9	200.7	1.9	4.3
	324.9	4.7	10.7
IIb-10	28.9	4.4	7.2
	25.3	4.1	3.8
IIb-11	146.3	5.4	12.7
	53.2**	1.2	3.4
IIb-12	84.4	1.5	9.0
	104.5	2.0	6.8
IIb-13	71.4	2.7	11.8
	4.7*	-	-
IIb-14	-**	-	-
	-**	-	-
IIb-15	53.4	3.3	3.0
	5.6*	-	-
IIb-16	64.3	3.5	4.4
	35.8	1.6	3.1
IIb-17	52.8	2.5	13.1
	64.9	3.3	9.4

*Specimen broke in shoulder.
**Defective Specimen.

TABLE 24

1400°F/90,000 psi (760°C/621 MN/m^2) Stress Rupture Properties For Task I Extruded Plus Rolled Material Subjected to a Partial Solution Heat Treatment

Composition Number	Rupture Life (hours)	Elongation (%)	Reduction of Area (%)
IIb-1	26.2	23.8	32.1
	26.8	28.0	38.7
IIb-2	14.0	9.1	19.5
	11.4	9.0	23.9
IIb-3	10.3*	13.9	0.9
	11.0	6.4	5.5
IIb-4	15.0	11.4	10.9
	15.7	7.2	7.2
IIb-5	8.6	14.4	22.4
	9.3	6.8	19.5
IIb-6	16.2	15.6	18.1
	13.4	9.6	24.3
IIb-7	18.6	15.4	22.3
	19.7	20.1	20.1
IIb-8	23.9	13.9	19.1
	37.9	14.0	20.7
IIb-9	15.7	9.1	20.7
	13.9	8.9	27.0
IIb-10	28.9	4.4	7.2
	25.3	4.1	3.8
IIb-11	12.7	13.0	21.2
	13.0	15.9	21.6
IIb-12	26.7	23.6	28.1
	8.1	7.0	13.8
IIb-13	18.7	18.2	21.6
IIb-14	- ***	-	-
	- ***	-	-
IIb-15	7.3	16.5	18.2
	6.9	18.1	25.6
IIb-16	5.9	15.3	20.5
	7.1	13.3	15.9
IIb-17	11.9	14.5	18.1
	10.3	14.5	25.3

*Specimen broke in shoulder.
***Specimen broke on loading.

TABLE 25

Room Temperature Tensile Properties For Task I Extruded Materials Subjected to a Full Solution Heat Treatment and Exposed at 1600°F (871°C) For 1500 Hours

Composition Number	Ultimate Tensile Strength (KSI)	Ultimate Tensile Strength (MN/m^2)	0.2% Yield Strength (KSI)	0.2% Yield Strength (MN/m^2)	Elongation (%)	Reduction Of Area (%)
IIb-1	199.8	1378	122.5	845	16.8	24.5
	199.2	1373	122.6	845	18.1	23.1
IIb-2	190.1	1311	131.3	905	9.4	12.6
	193.4	1333	134.0	924	12.4	15.7
IIb-3	159.7	1101	143.4	989	3.3	6.9
	161.9	1116	143.5	989	3.1	5.9
IIb-4	195.0	1345	120.9	834	18.3	22.9
	192.5	1327	120.1	828	16.7	22.8
IIb-5	181.1	1249	151.4	1044	1.7	6.3
	169.7	1170	156.0	1076	2.8	4.1
IIb-6	194.0	1138	147.5	1017	8.6	10.0
	204.0	1407	145.6	1004	10.9	14.7
IIb-7	187.8	1295	151.7	1046	7.0	13.7
	182.6	1259	150.9	1040	5.7	7.7
IIb-8	213.8	1474	150.2	1036	11.5	11.5
	210.0	1448	148.2	1022	11.3	12.4
IIb-9	129.6**	894	--	--	1.9	4.5
	149.3	1029	144.4	996	2.3	7.9
IIb-10	192.3	1326	131.1	904	15.5	13.4
	190.5	1313	128.6	887	15.0	12.9
IIb-11	167.2	1153	152.9	1054	3.4	4.0
	156.9	1082	151.9	1047	1.5	4.3
IIb-12	93.5	645	93.5	645	0.6	1.2
	19.5**	134	--	--	-	-
IIb-13	158.5	1093	155.0	1069	1.5	1.2
	155.3	1071	153.5	1058	1.3	4.4
IIb-14	66.3**	457	--	--	-	-
	117.6	811	117.6	811	1.1	1.5
IIb-15	46.1*	318	46.1	318	-	-
	90.6*	625	90.6	625	-	-
IIb-16	125.8*	867	125.8	867	-	-
	87.1**	601	--	--	-	-
IIb-17	160.7	1108	147.9	1020	2.9	5.8
	189.9	1309	148.6	1025	9.3	12.0

*Specimen broke in shoulder.
**Defective Specimen.

TABLE 26

X-Ray Diffraction Studies of Residues Extracted From Task I Extruded Alloys After Full Solution Heat Treatment and Exposure

Alloy Designation	Relative Concentration* of Phases Present			
	MC	M_6C	$M_{23}C_6$	Mu-Phase
IIb-1	VS**		W	
IIb-2	VS**		W	
IIb-3	VS**	W	W	
IIb-4	VS	M	W	
IIb-5	VS		M	
IIb-6	VS		M	
IIb-7	M	S		
IIb-8	VS	W		
IIb-9	VS		M	
IIb-10	VS**		S	
IIb-11	M	M	M	S
IIb-12	S	W	M	M
IIb-13	S	W	S	
IIb-14	S		M	
IIb-15	VW			VS
IIb-16	M		M	VS
IIb-17	VS**	M	M	

*S represents Strong; M, Moderate; W, Weak; and V, Very.
**Indicates two distinct MC-type carbides.

TABLE 27

Chemical Analyses of Two Task II Heats

Alloy Designation	Heat Numbers	Chemical Composition (weight percent) for: C	Cr	Co	Mo	W	Ta	Al	Ti	B	Zr	V	Hf	Ni
IIb-H (Aim)		0.115	9.00	9.00	2.00	7.88	6.63	4.38	0.75	0.020	0.100	0.50	0.81	Bal
(KB2566)	KC1766 & 1767	0.110	9.02	9.15	1.82	7.98	6.57	4.28	0.73	0.020	0.095	0.48	0.73	Bal
IIb-L (Aim)		0.115	9.00	9.00	2.00	7.88	10.38	3.38	0.75	0.020	0.100	0.50	0.81	Bal
(KB2567)	KC1768 & 1769	0.113	8.86	8.95	1.76	8.05	10.48	3.43	0.74	0.021	0.102	0.47	0.83	Bal

TABLE 28

Optimum Heat Treatments* Developed For IIb-H and IIb-L

Full Solution Heat Treatment For IIb-H

2225°F/2 hours/RAC + 1650°F/16 hours/RAC + 1400°F/16 hours/AC
1219°C/2 hours/RAC + 899°C/16 hours/RAC + 760°C/16 hours/AC

Partial Solution Heat Treatment For IIb-L

1600°F/16 hours + increase to 2000°F/1 hour/OQ + 1400°F/16 hours
871°C/16 hours + increase to 1093°C/1 hour/OQ + 760°C/16 hours

*RAC indicates Rapid Air Cool; AC, Air Cool; and OQ, Oil Quench.

TABLE 29

X-Ray Diffraction Studies of Residues Extracted From As-Heat Treated and From As-Heat Treated Plus Exposed IIb-H and IIb-L

Alloy Designation	Thermal Exposure	Relative Concentration* of Phases Present			
		MC	M_6C	$M_{23}C_6$	Mu-Phase
IIb-H	None	VS**	M		
IIb-H	1600°F/1500 hours (871°C/1500 hours)	M	VS		
IIb-L	None	M	VVS		
IIb-L	1300°F/1500 hours (704°C/1500 hours)	M	VS	M	M

*S represents Strong; M, Moderate; W, Weak; and V, Very.

**Indicates two distinct MC-type carbides.

TABLE 30

Tensile Properties For IIb-H

Test Temperature (°F)	Test Temperature (°C)	Ultimate Tensile Strength (KSI)	Ultimate Tensile Strength (MN/m²)	0.2% Yield Strength (KSI)	0.2% Yield Strength (MN/m²)	Elongation (%)	Reduction Of Area (%)
Room	Room	228.4	1575	173.0	1193	14.6	15.6
Room	Room	224.5	1548	177.6	1225	13.8	12.4
Room	Room	253.2*	1746	-	-	-	-
Room	Room	250.1*	1724	-	-	-	-
1200	649	215.6	1487	167.0	1151	10.2	13.6
1200	649	- **	-	-	-	-	-
1400	760	185.0	1276	162.6	1121	12.0	12.4
1400	760	183.6	1266	161.3	1112	13.6	18.9
1400	760	201.9*	1392	-	-	-	-
1600	871	138.1	952	122.2	843	6.3	7.4
1600	871	- **	-	-	-	-	-
1800	982	78.8	543	64.3	443	2.8	3.8
1800	982	37.6**	359	37.6	259	0.9	3.8
1800	982	81.3*	561	-	-	-	-
1800	982	66.4*	458	-	-	-	-

*Notched tensile test.
**Defective specimen.

TABLE 31

Tensile Properties For IIb-L

Test Temperature (°F)	Test Temperature (°C)	Ultimate Tensile Strength (KSI)	Ultimate Tensile Strength (MN/m^2)	0.2% Yield Strength (KSI)	0.2% Yield Strength (MN/m^2)	Elongation (%)	Reduction Of Area (%)
Room	Room	281.5	1941	253.0	1744	6.7	9.9
Room	Room	254.3	1753	252.3	1740	2.2	4.4
Room	Room	317.2*	2187	-	-	-	-
Room	Room	300.9*	2075	-	-	-	-
1200	649	257.1	1773	234.2	1615	5.0	10.7
1200	649	253.9	1751	230.9	1592	6.1	10.6
1200	649	242.7*	1673	-	-	-	-
1200	649	242.7*	1673	-	-	-	-
1300	704	219.6	1514	216.1	1490	1.8	2.6
1300	704	- **	-	-	-	-	-
1400	760	209.4	1444	196.0	1351	4.9	6.5
1400	760	214.6	1480	197.4	1361	3.0	5.3
1400	760	231.5*	1596	-	-	-	-
1400	760	215.7*	1487	-	-	-	-
1800	982	29.8	305	13.3	92	62.6	94.5
1800	982	28.3	195	16.1	111	56.1	96.0

*Notched tensile test.
**Defective specimen.

TABLE 32

Stress and Creep Rupture Properties For IIb-H

Test Temperature (°F)	Test Temperature (°C)	Stress (KSI)	Stress (MN/m^2)	Rupture Life (hours)	Time To 0.2% Creep (hours)	Elongation (%)	Reduction Of Area (%)
1400	760	90	621	254.4	-	2.7	3.2
1400	760	90	621	214.8	-	3.5	4.6
1400	760	90	621	-	34.5	-	-
1500	816	70	483	128.7	-	2.6	5.4
1500	816	70	483	108.2	-	2.9	2.3
1600	871	55	379	37.7	-	3.3	6.1
1600	871	55	379	35.3	-	4.0	2.9
1800	982	25	172	23.0	-	10.9	12.9
1800	982	25	172	13.5	-	15.7	16.4

TABLE 33

Stress and Creep Rupture Properties For IIb-L

Test Temperature (°F)	(°C)	Stress (KSI)	(MN/m²)	Rupture Life (hours)	Time To 0.2% Creep (hours)	Elongation (%)	Reduction Of Area (%)
1000	538	160	1103	-	1000*	-	-
1000	538	160	1103	-	1000*	-	-
1200	649	175	1207	58.7	-	2.6	6.7
1200	649	175	1207	- **	-	-	-
1300	704	125	862	28.6	-	8.0	11.9
1300	704	125	862	41.7	-	6.9	9.6
1400	760	90	621	17.8	-	27.7	34.5
1400	760	90	621	13.5	-	15.5	17.8

*Test was discontinued after 1000 hours with no creep.
**Defective specimen.

TABLE 34

Room Temperature Tensile Properties For IIb-H and IIb-L
Before and After 1500 Hours Exposure

Alloy Designation	Thermal Exposure	Ultimate Tensile Strength (KSI)	Ultimate Tensile Strength (MN/m^2)	0.2% Yield Strength (KSI)	0.2% Yield Strength (MN/m^2)	Elongation (%)	Reduction Of Area (%)
IIb-H	None	228.4	1575	173.0	1193	14.6	15.6
		224.5	1548	177.6	1225	13.8	12.4
IIb-H	1600°F/1500 hours	192.0	1324	136.4	941	10.9	7.1
	(871°C/1500 hours)	188.1	1297	135.6	935	9.9	11.6
IIb-L	None	281.5	1941	253.0	1744	6.7	9.9
		254.3	1753	252.3	1740	2.2	4.4
IIb-L	1300°F/1500 hours	277.7	1915	257.8	1778	4.6	6.3
	(704°C/1500 hours)	273.2	1884	258.4	1782	2.9	6.2

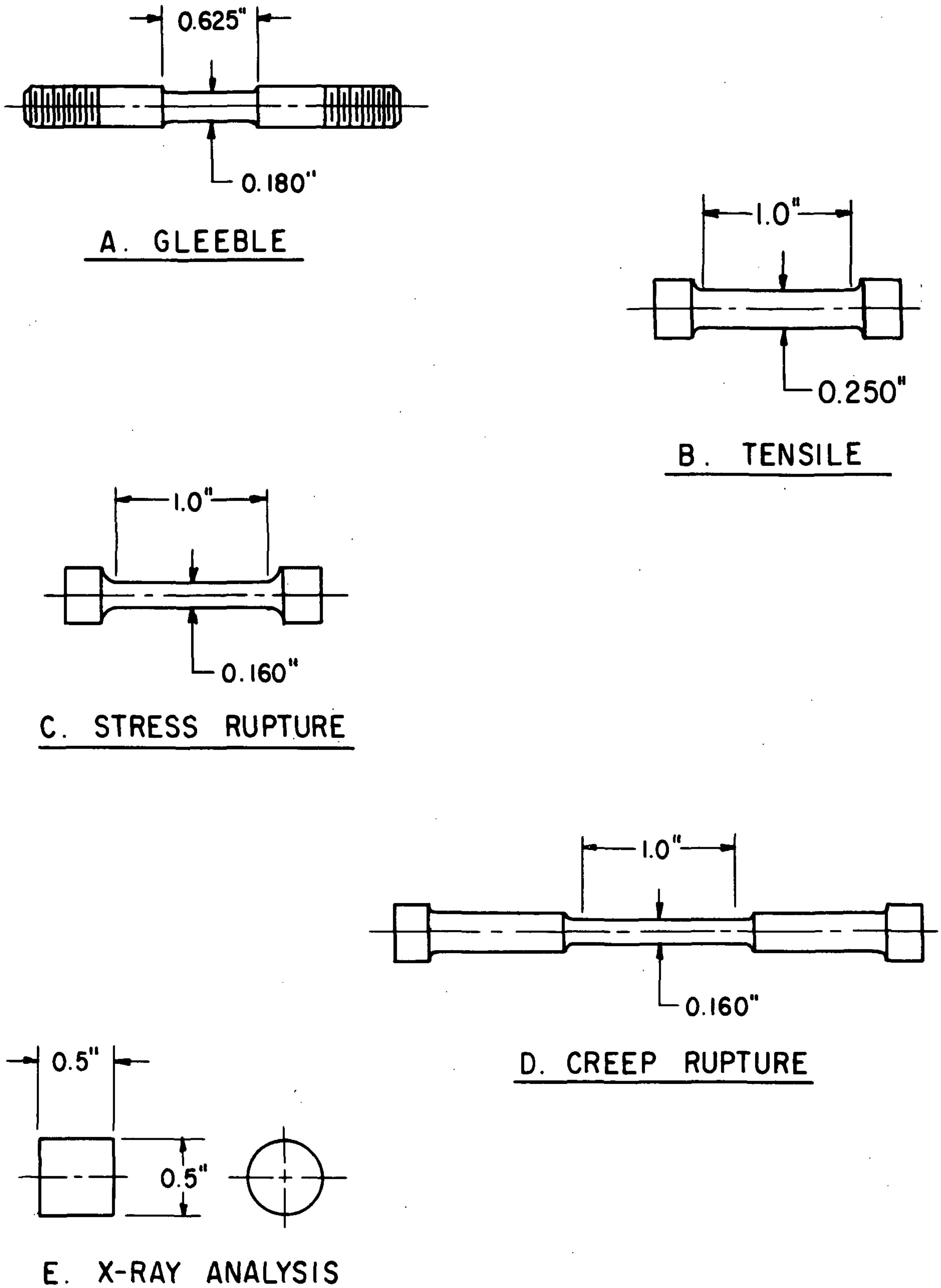


FIGURE 1 : TEST SPECIMEN CONFIGURATIONS

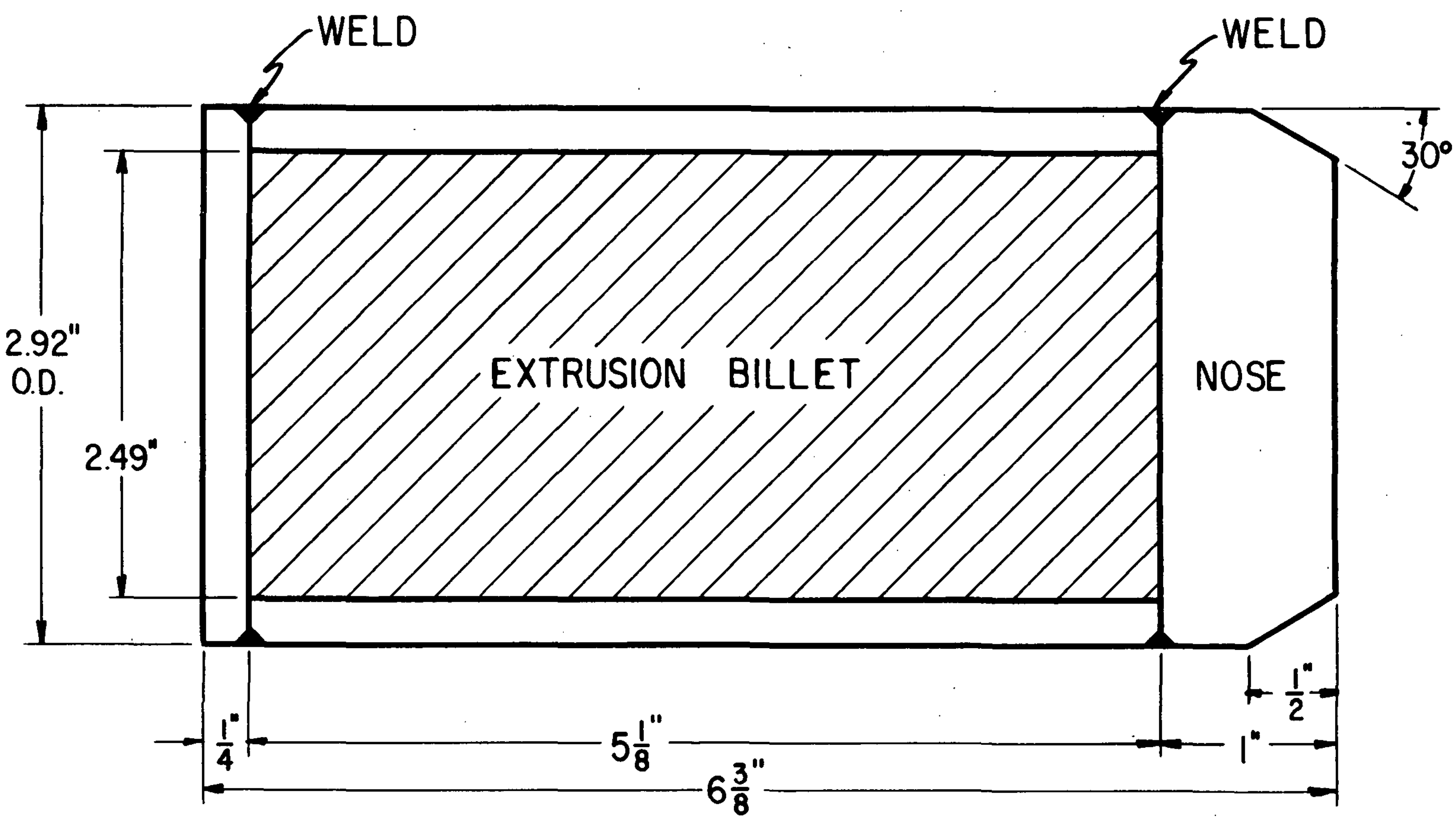


FIGURE 2: SCHEMATIC DIAGRAM OF CANNED BILLET FOR EXTRUSION AT THE AIR FORCE MATERIALS LABORATORY.

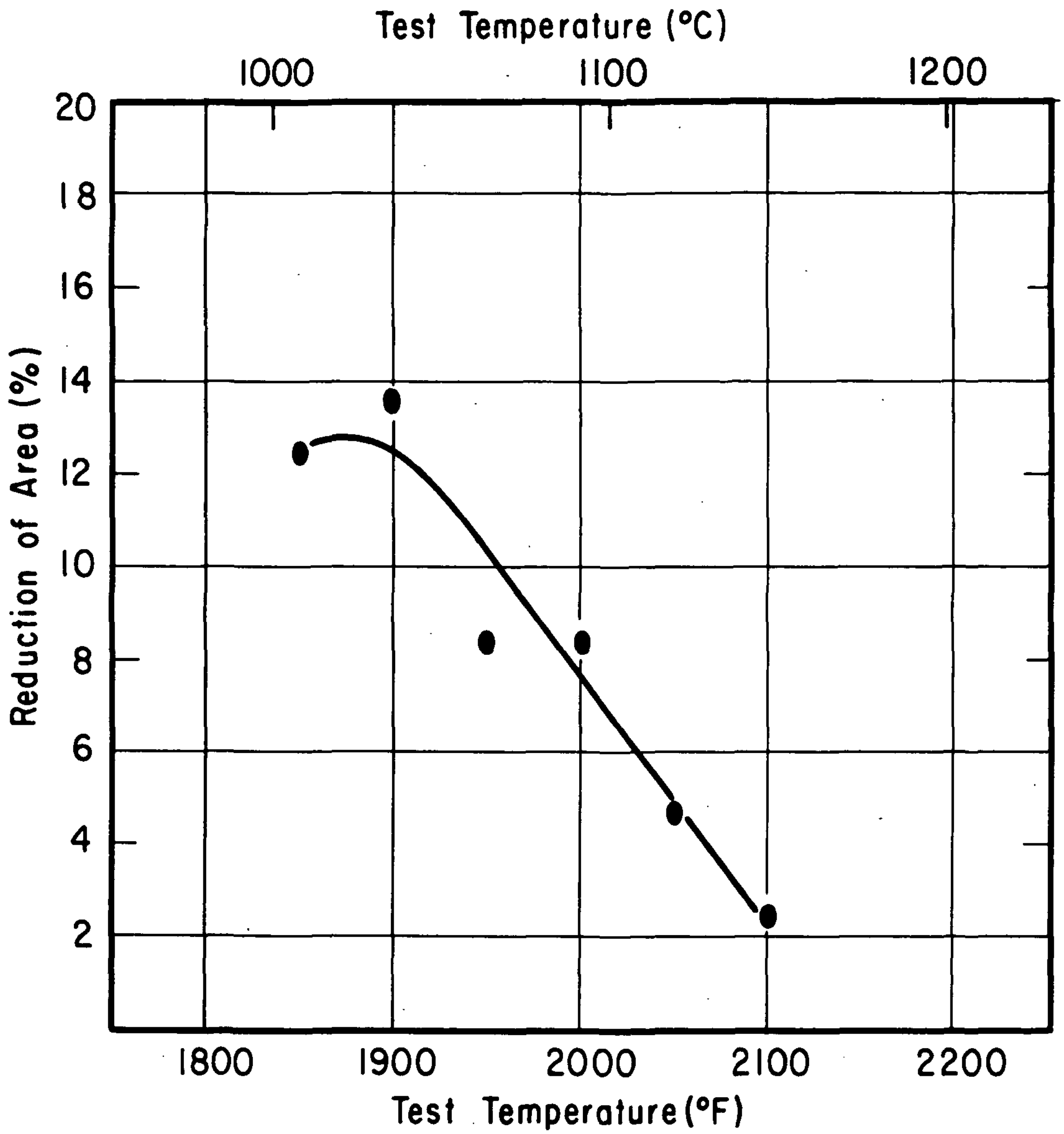
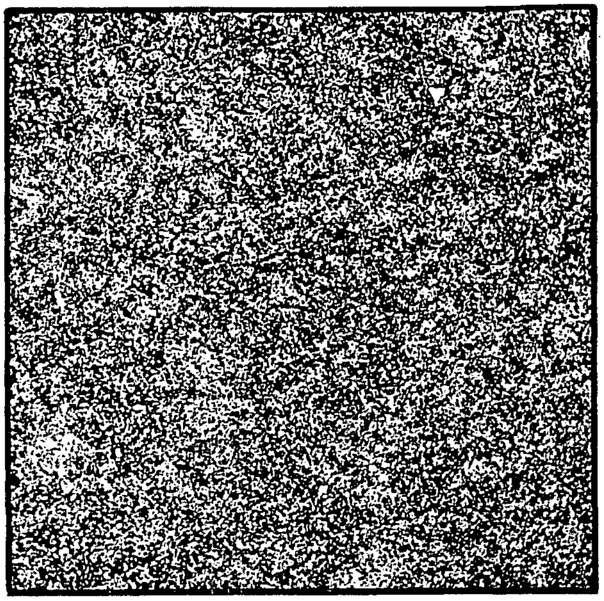


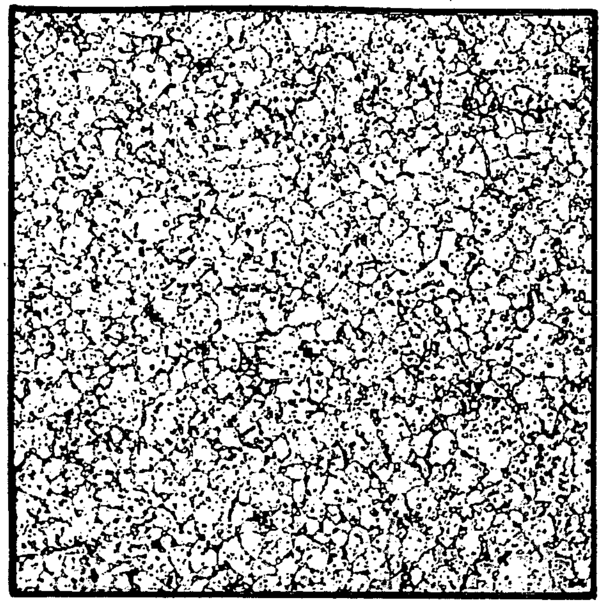
FIGURE 3: GLEEBLE INHERENT DUCTILITY CURVE FOR AS-CAST IIb-3.



R23899 200X

2150°F (1177°C) / 2 hours

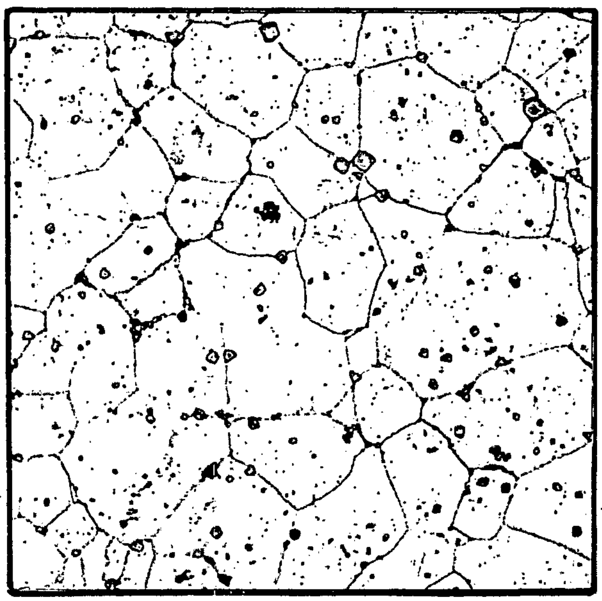
Grain Size : Unrecrystallized



R23901 200X

2225°F (1219°C) / 2 hours

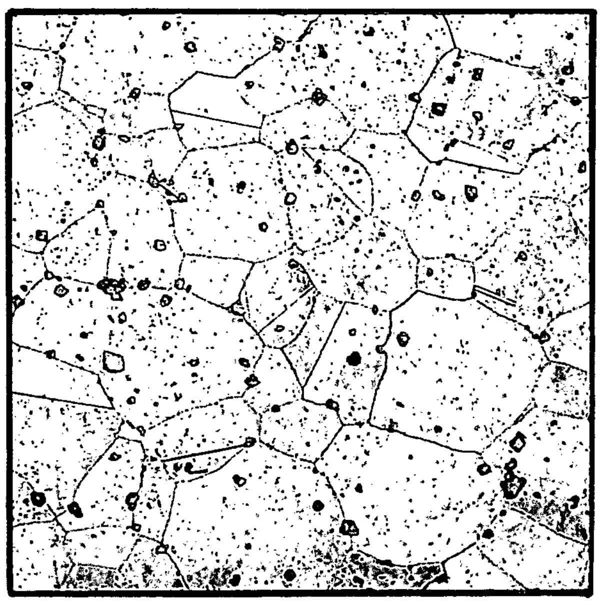
Grain Size : ASTM 8 to 9



R23924 200X

2250°F (1232°C) / 2 hours

Grain Size : ASTM 5 to 6

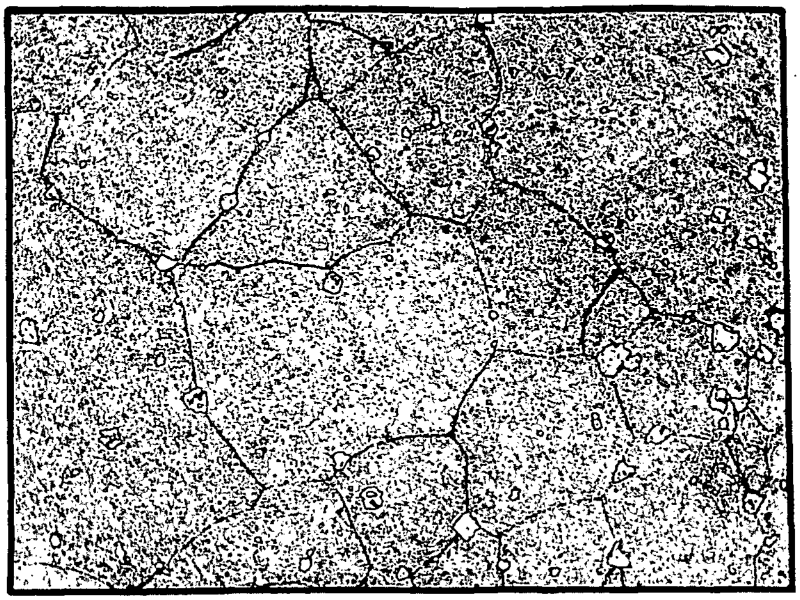


R23925 200X

2250°F (1232°C) / 4 hours

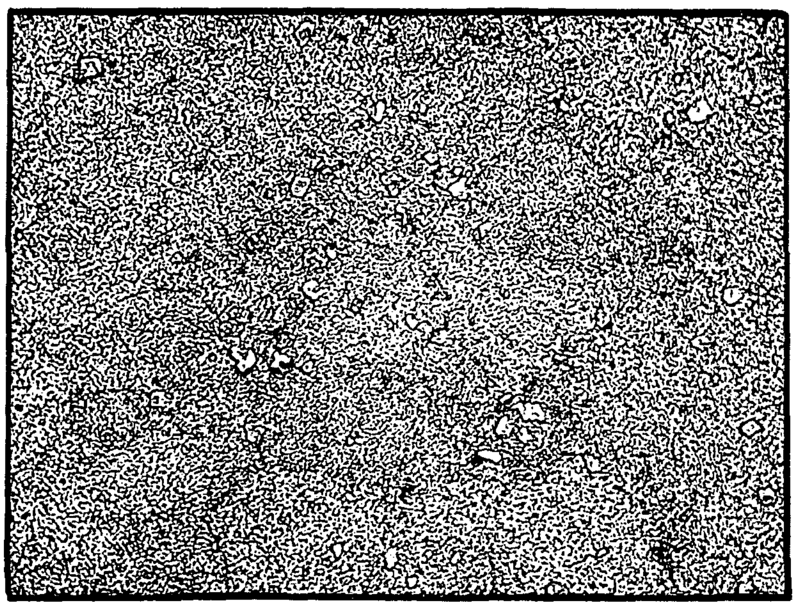
Grain Size : ASTM 4 to 5

FIGURE 4 : PHOTOMICROGRAPHS ILLUSTRATING THE EFFECT OF VARIOUS FULL SOLUTION TREATMENTS ON GRAIN SIZE FOR EXTRUDED PLUS ROLLED IIb-17.



R23732 OPTIMUM 500X

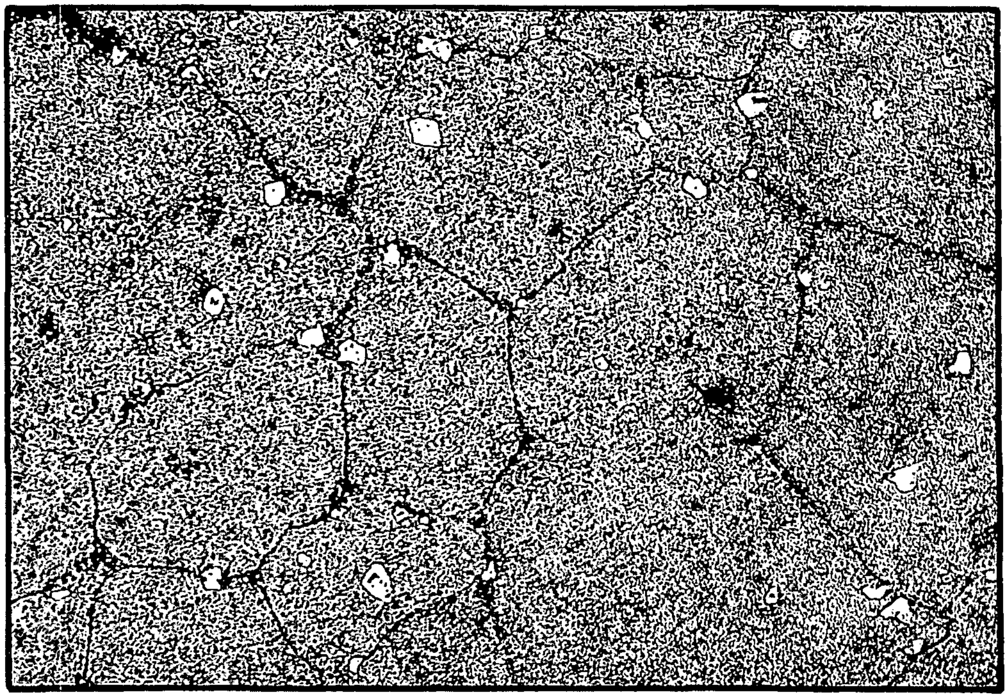
2250°F / 4 hours + 1600°F / 16 hours
(1232°C / " + 871°C / ")



R23734 OVERAGED 500X

2250°F / 4 hours + 1900°F / 16 hours
(1232°C " + 1038°C ")

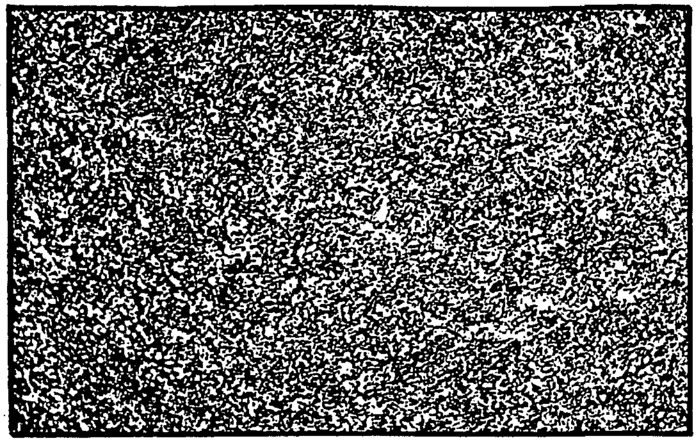
FIGURE 5 : PHOTOMICROGRAPHS ILLUSTRATING THE EFFECT OF TWO INTERMEDIATE AGING TREATMENTS ON GAMMA PRIME MORPHOLOGY FOR EXTRUDED PLUS ROLLED IIb-8.



R 23930 IIb-17 500X

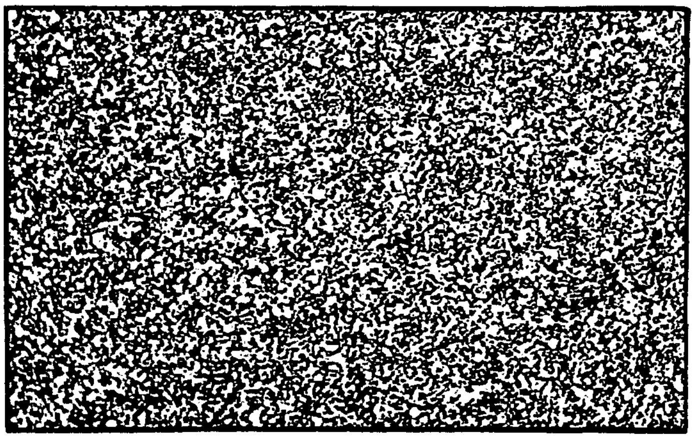
2250°F / 2 hours + 1600°F/16 hours + 1400°F/16 hours
1232°C / " + 871°C / " + 760°C / "

FIGURE 6 : PHOTOMICROGRAPH ILLUSTRATING THE OPTIMUM FINAL AGING TREATMENT FOR EXTRUDED PLUS ROLLED IIb-17.



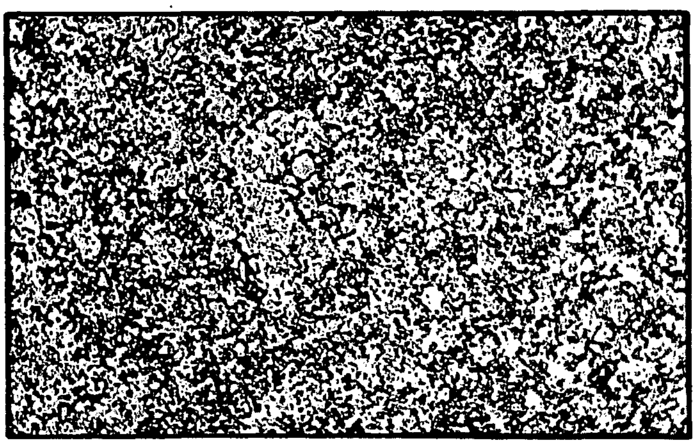
R23736 500X

2000°F (1093°C) / 1 hour / Oil Quench



R23737 500X

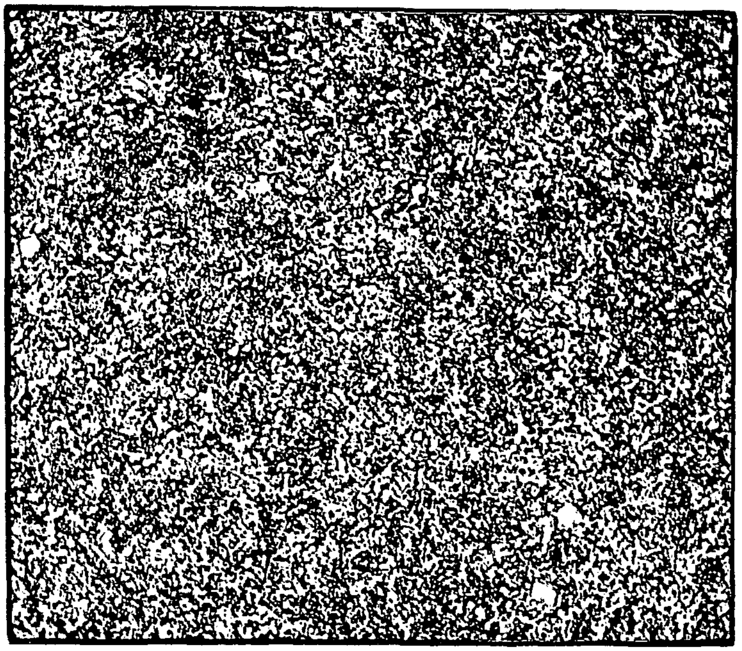
2050°F (1121°C) / 1 hour / Oil Quench



R23738 500X

2100°F (1149°C) / 1 hour / Oil Quench

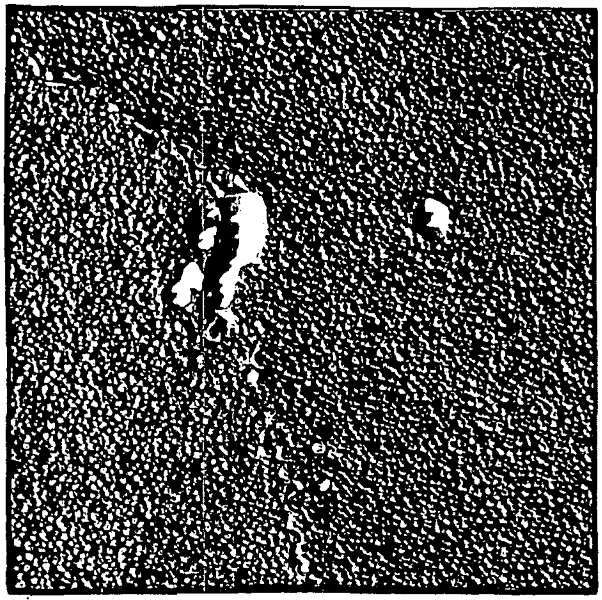
FIGURE 7: PHOTOMICROGRAPHS ILLUSTRATING THE EFFECT OF THREE PARTIAL SOLUTION TREATMENTS ON THE DEGREE OF SOLUTIONING FOR EXTRUDED PLUS ROLLED IIb-7.



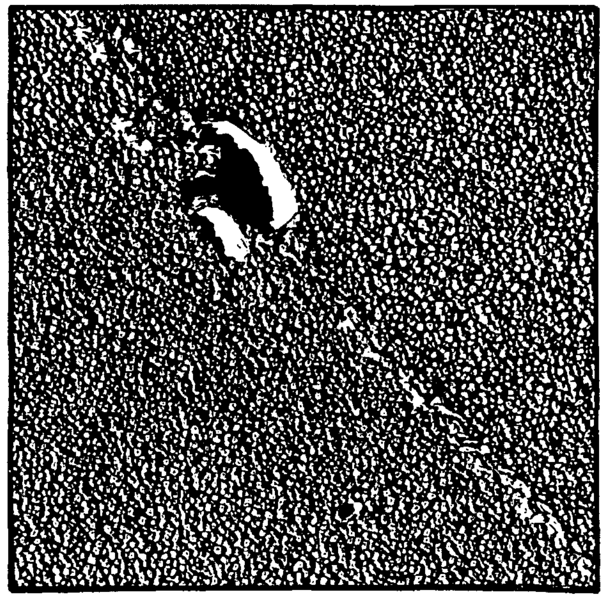
R23739 500X

1600°F/1 hour - increase to 2000°F/1 hour/oil quench + 1400°F/16 hours/AC
871°C/ " - " " 1093°C/ " / " " + 760°C/ " / "

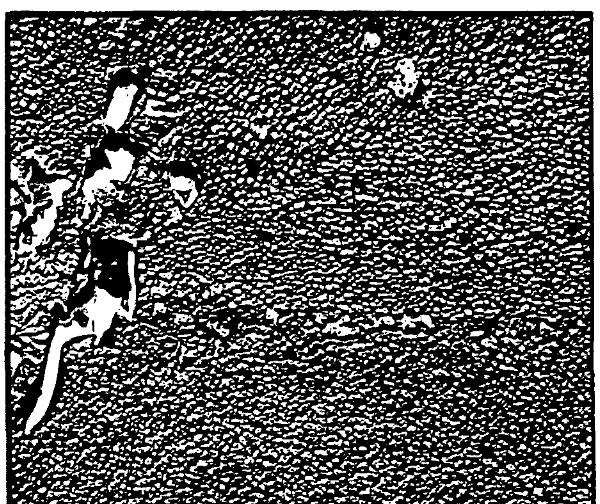
FIGURE 8: PHOTOMICROGRAPH ILLUSTRATING THE OPTIMUM PARTIAL SOLUTION HEAT TREATMENT FOR EXTRUDED PLUS ROLLED IIb-7.



EM3305 5000X



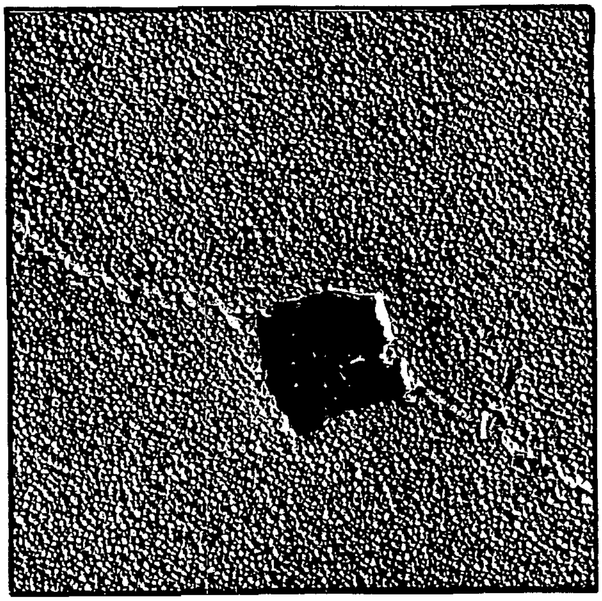
EM3306 5000X



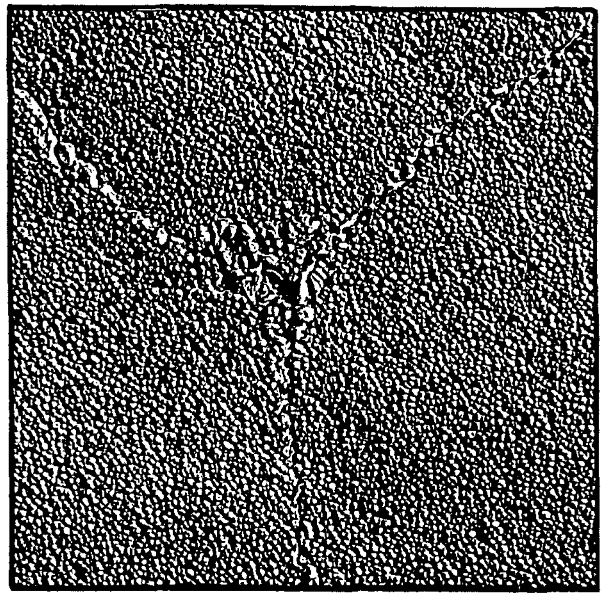
EM3307 5000X

FIGURE 9: ELECTRON MICROGRAPHS ILLUSTRATING THE STRUCTURE OF IIb-7 AFTER FULL SOLUTION HEAT TREATMENT.

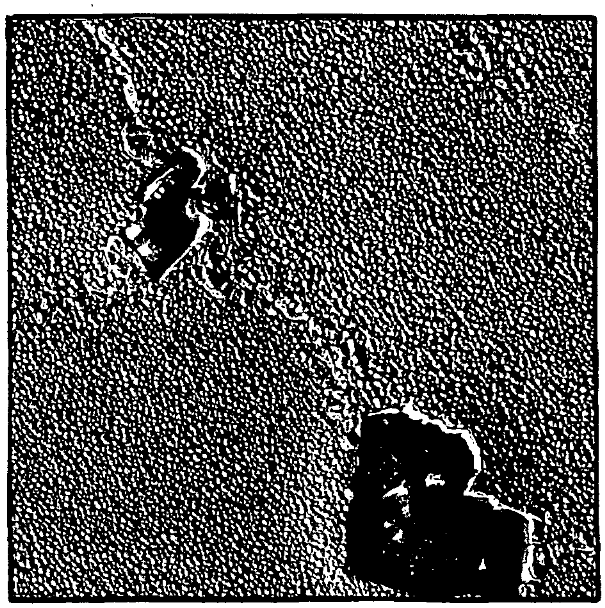
2250°F / 2hrs / RAC + 1600°F/16hrs/ RAC + 1400°F/16hrs/AC
1232°C/ " / " + 871°C/ " / " + 760°C/ " / "



EM3266 5000X



EM3272 5000X



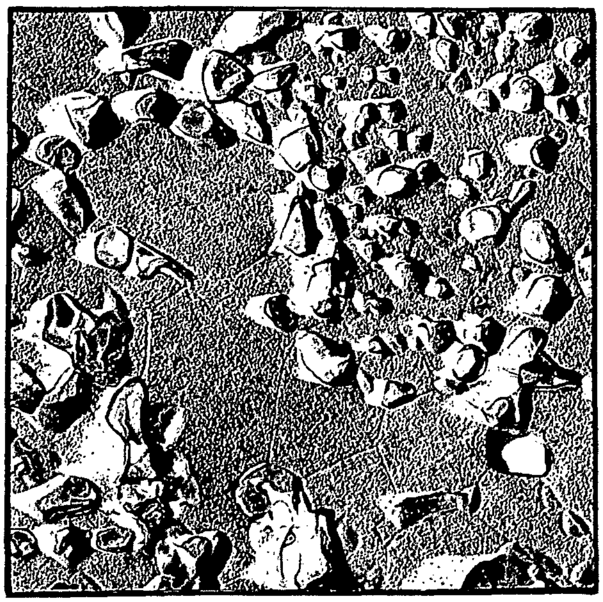
EM3269 5000X

FIGURE 10: ELECTRON MICROGRAPHS ILLUSTRATING THE STRUCTURE OF IIb-11 AFTER FULL SOLUTION HEAT TREATMENT

2250°F/2hrs/RAC + 1600°F/16hrs/RAC + 1400°F/16hrs/AC
1232°C/ " / " + 871°C/ " / " + 760°C/ " / "

EM3686 5000X

EM3684 5000X



EM3693 10,000X

FIGURE 11 : ELECTRON MICROGRAPHS ILLUSTRATING THE STRUCTURE OF IIb-7 AFTER PARTIAL SOLUTION HEAT TREATMENT.

1600°F/16hrs + increase to 2000°F/1hr/OQ + 1400°F/16hrs/AC
871°C/ " + " " 1093°C/ " / " + 760°C/ " / "

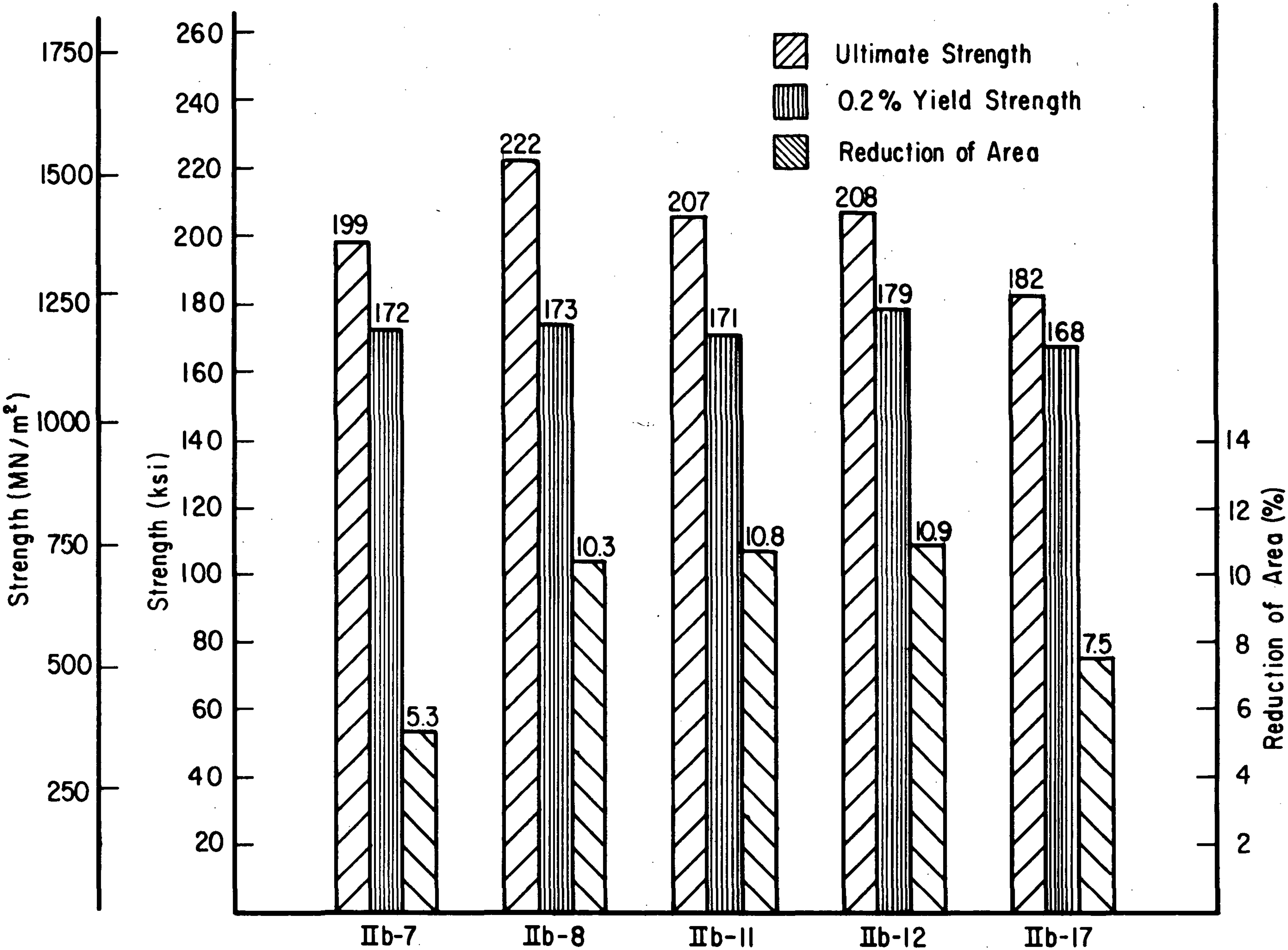


FIGURE 12: ROOM TEMPERATURE TENSILE PROPERTIES FOR FIVE BEST TASK I ALLOYS IN THE EXTRUDED CONDITION AND SUBJECTED TO A FULL SOLUTION HEAT TREATMENT.

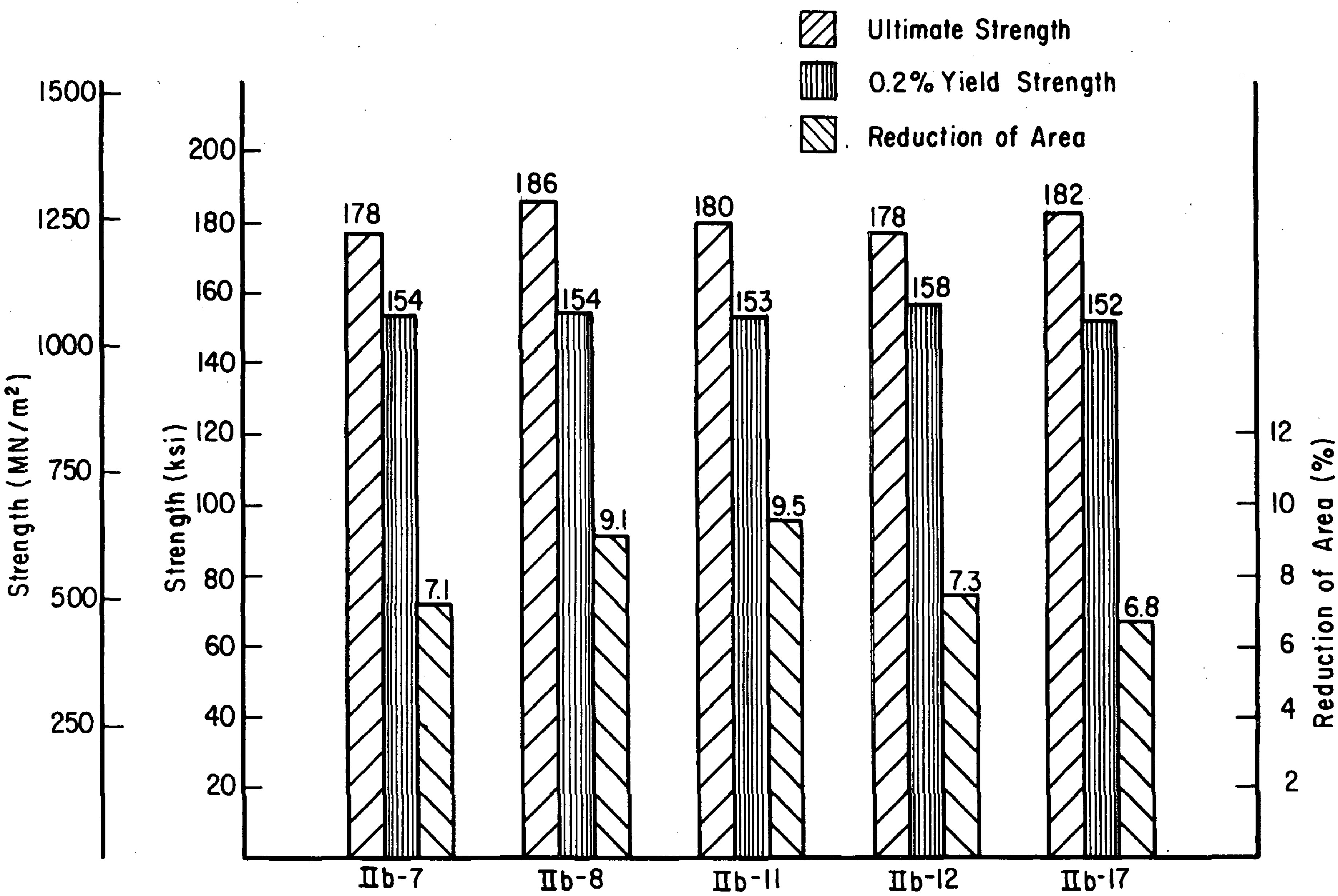


FIGURE 13: 1400°F (760°C) TENSILE PROPERTIES FOR FIVE BEST TASK I ALLOYS IN THE EXTRUDED CONDITION AND SUBJECTED TO A FULL SOLUTION HEAT TREATMENT.

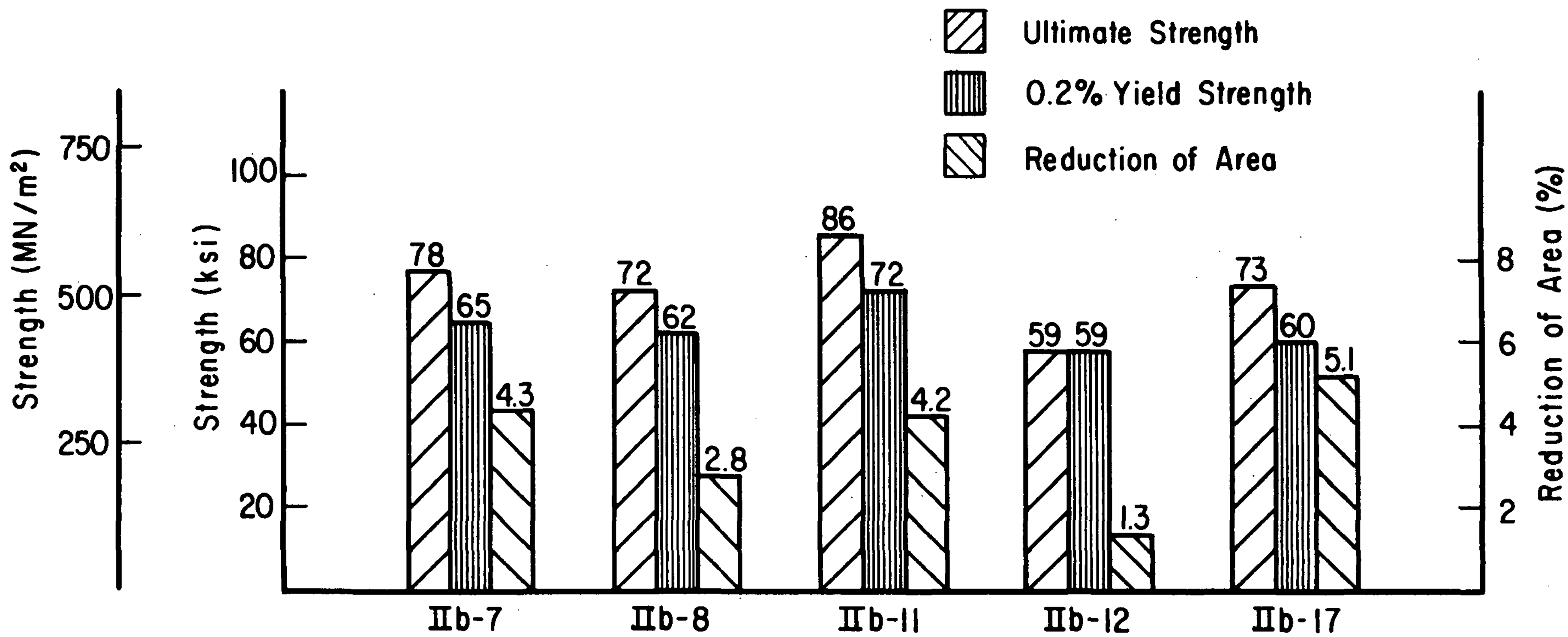


FIGURE 14: 1800°F (982°C) TENSILE PROPERTIES FOR FIVE BEST TASK I ALLOYS IN THE EXTRUDED CONDITION AND SUBJECTED TO A FULL SOLUTION HEAT TREATMENT.

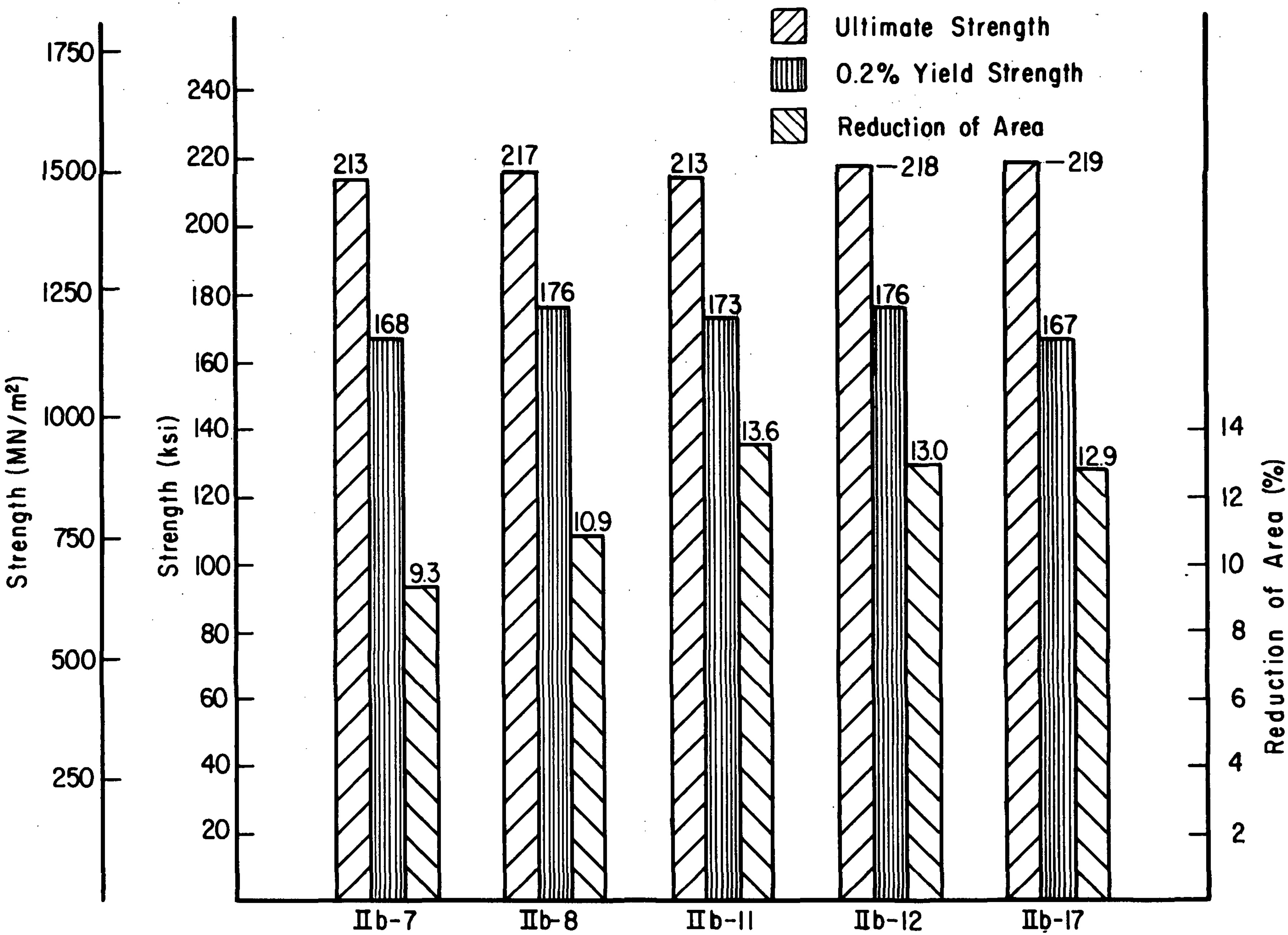


FIGURE 15: ROOM TEMPERATURE TENSILE PROPERTIES FOR FIVE BEST TASK I ALLOYS IN THE EXTRUDED PLUS ROLLED CONDITION AND SUBJECTED TO A FULL SOLUTION HEAT TREATMENT.

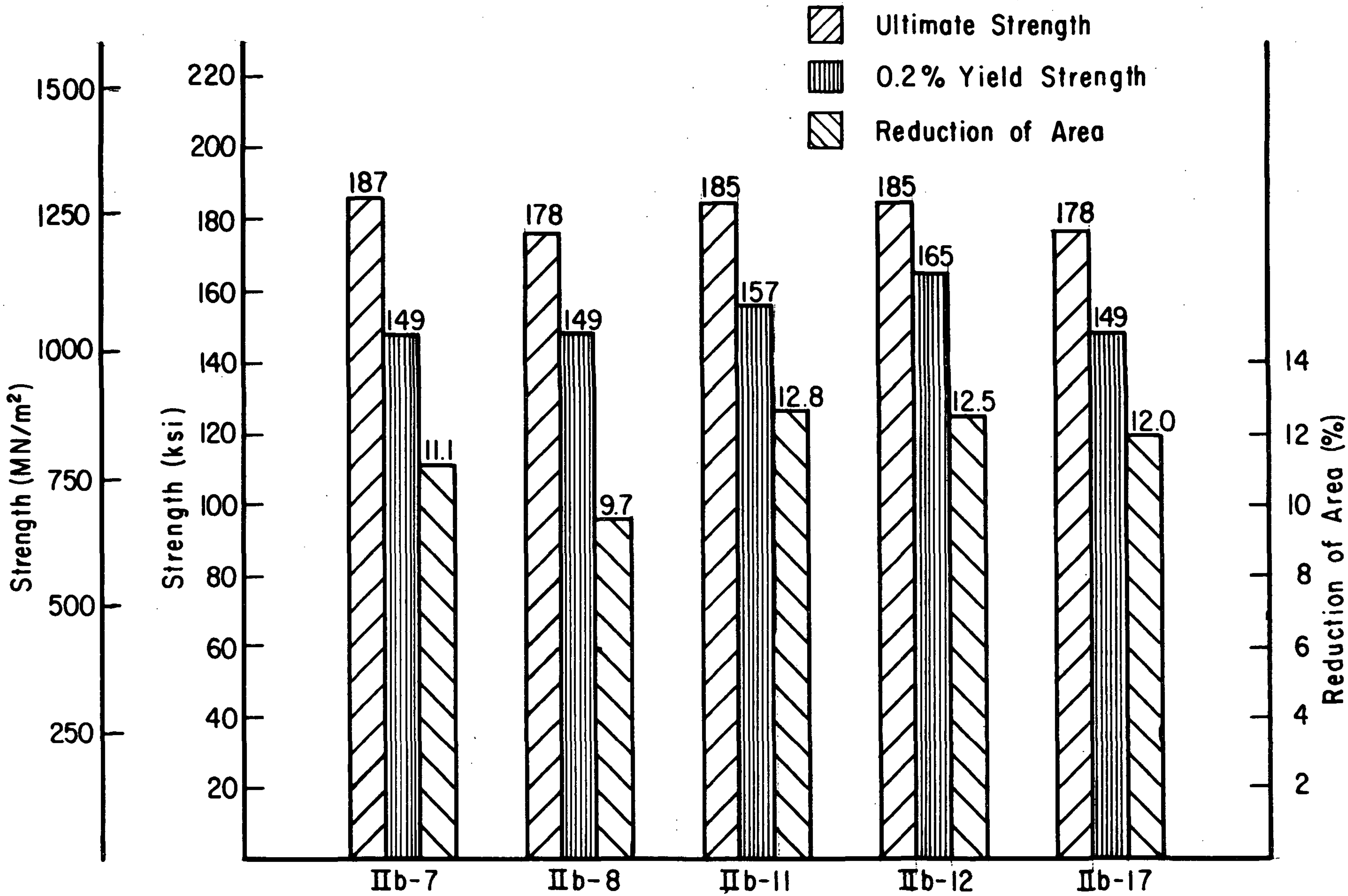


FIGURE 16: 1400°F (760°) TENSILE PROPERTIES FOR FIVE BEST TASK I ALLOYS IN THE EXTRUDED PLUS ROLLED CONDITION AND SUBJECTED TO A FULL SOLUTION HEAT TREATMENT.

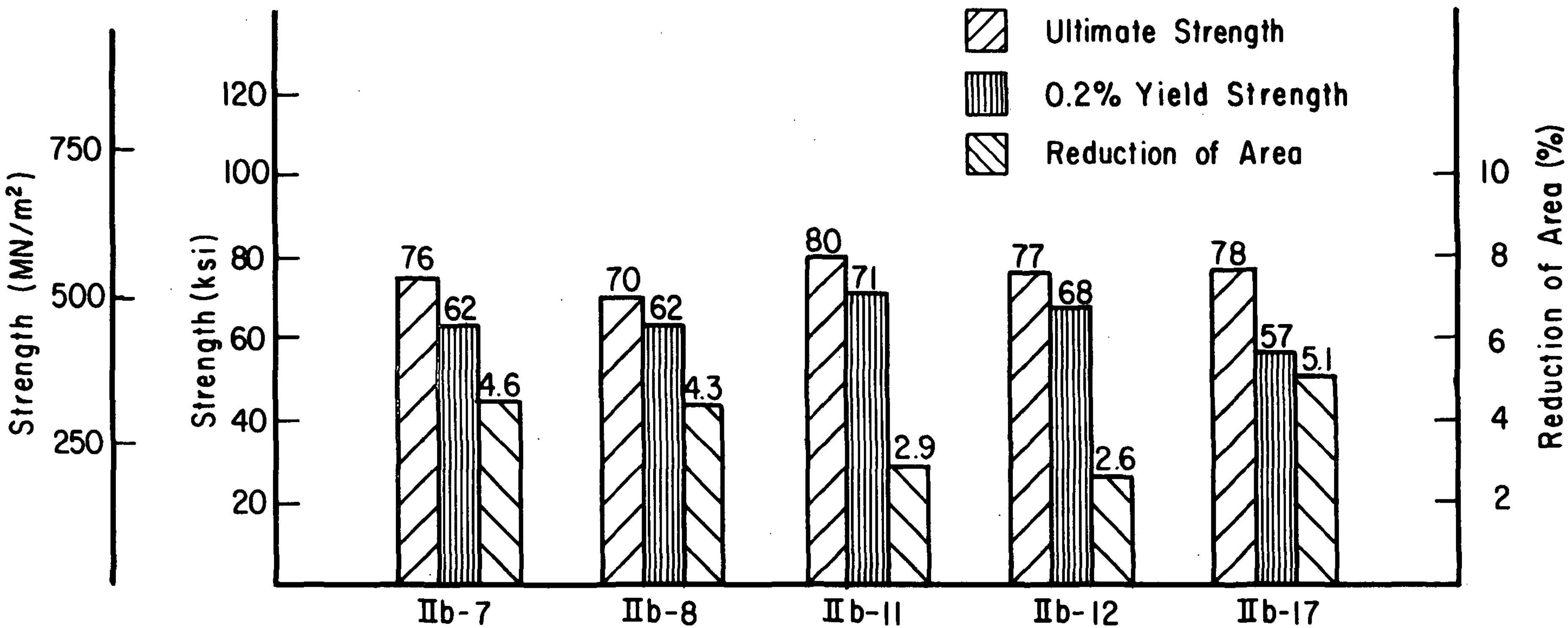


FIGURE 17: 1800°F (982°C) TENSILE PROPERTIES FOR FIVE BEST TASK I ALLOYS IN THE EXTRUDED PLUS ROLLED CONDITION AND SUBJECTED TO A FULL SOLUTION HEAT TREATMENT.

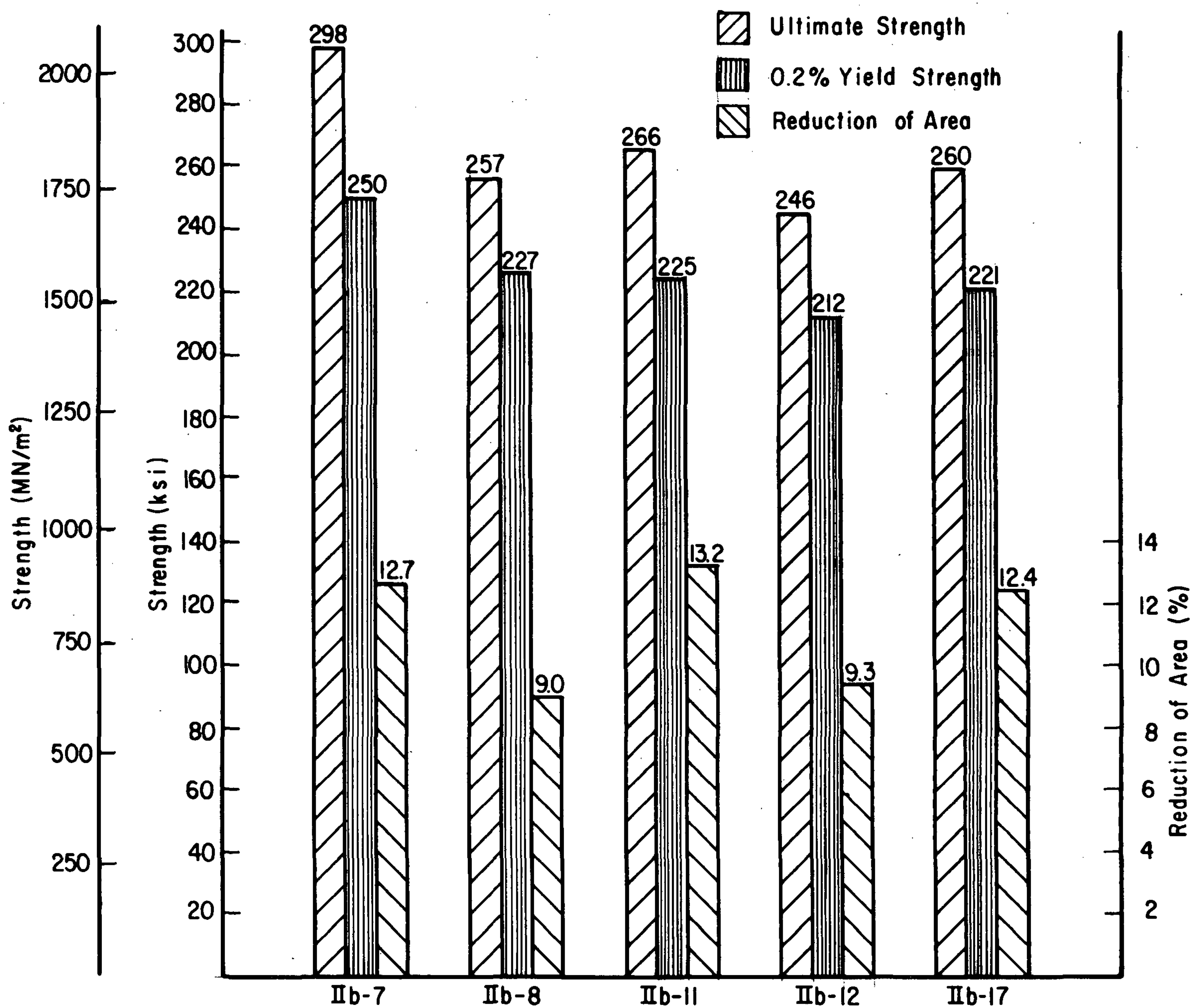


FIGURE 18 : ROOM TEMPERATURE TENSILE PROPERTIES FOR FIVE BEST TASK I ALLOYS IN THE EXTRUDED PLUS ROLLED CONDITION AND SUBJECTED TO A PARTIAL SOLUTION HEAT TREATMENT.

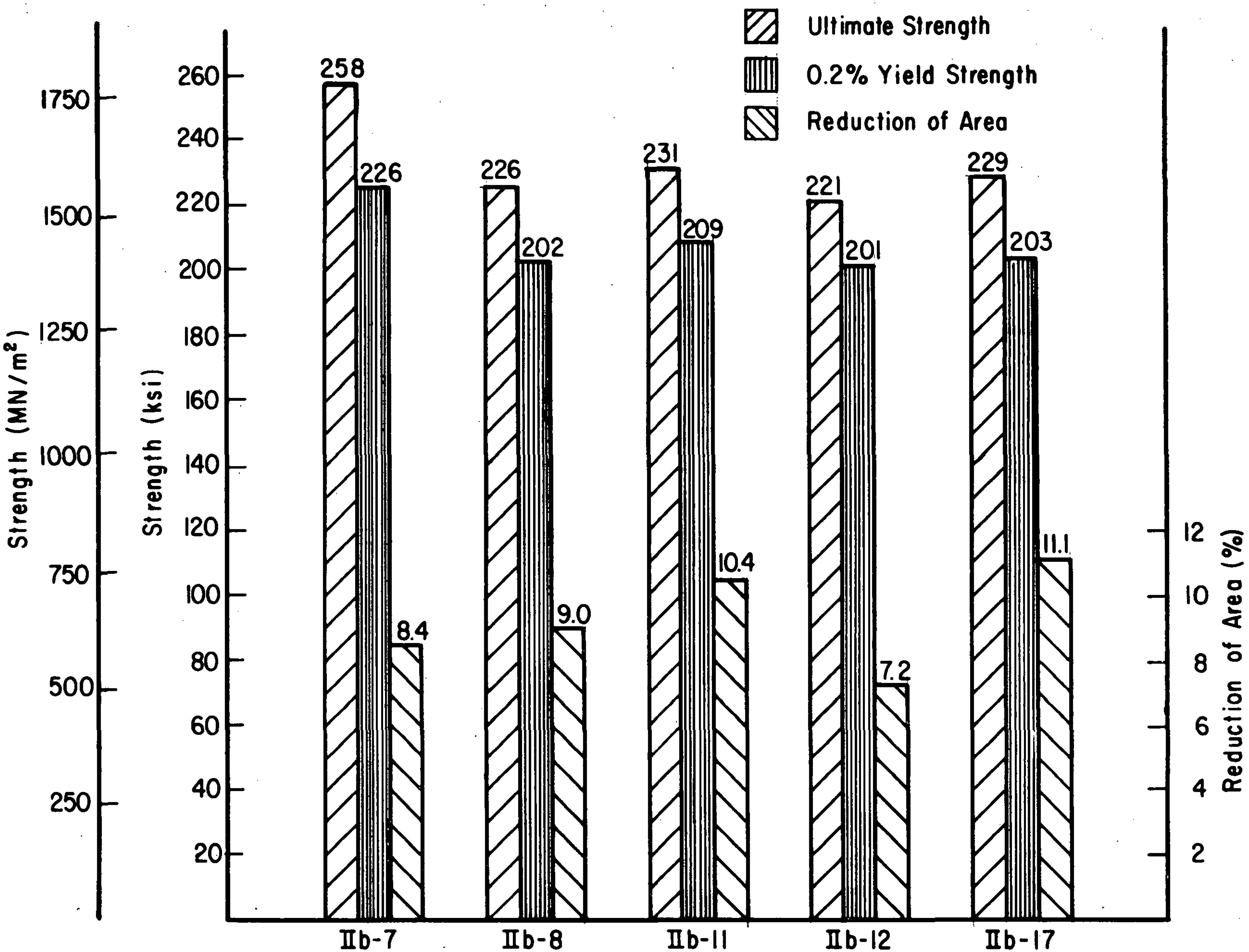


FIGURE 19 : 1200°F (649°C) TENSILE PROPERTIES FOR FIVE BEST TASK I ALLOYS IN THE EXTRUDED PLUS ROLLED CONDITION AND SUBJECTED TO A PARTIAL SOLUTION HEAT TREATMENT.

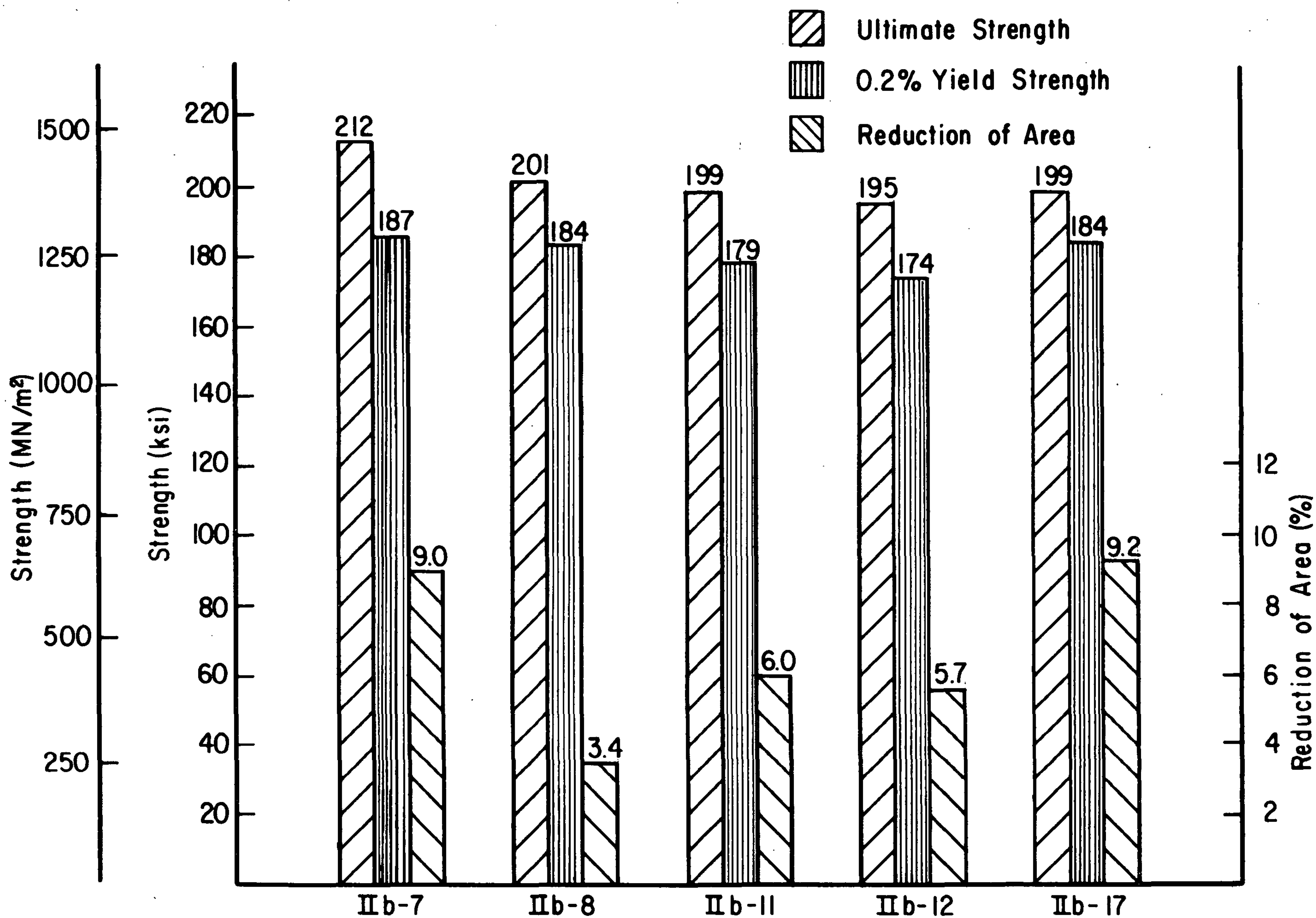


FIGURE 20: 1400°F (760°C) TENSILE PROPERTIES FOR FIVE BEST TASK I ALLOYS IN THE EXTRUDED PLUS ROLLED CONDITION AND SUBJECTED TO A PARTIAL SOLUTION HEAT TREATMENT.

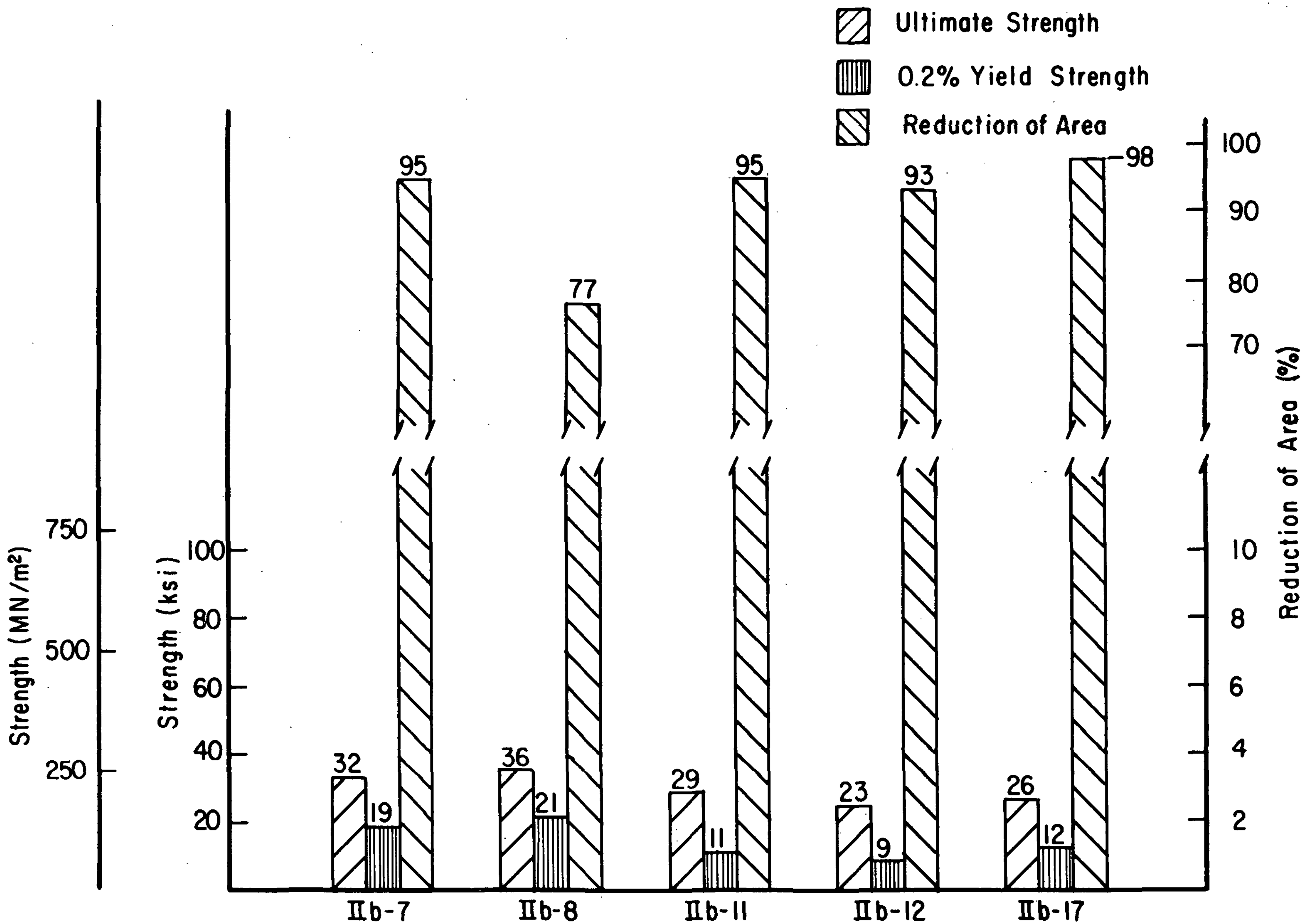


FIGURE 21 : 1800°F (982°C) TENSILE PROPERTIES FOR FIVE BEST TASK I ALLOYS IN THE EXTRUDED PLUS ROLLED CONDITION AND SUBJECTED TO A PARTIAL SOLUTION HEAT TREATMENT.

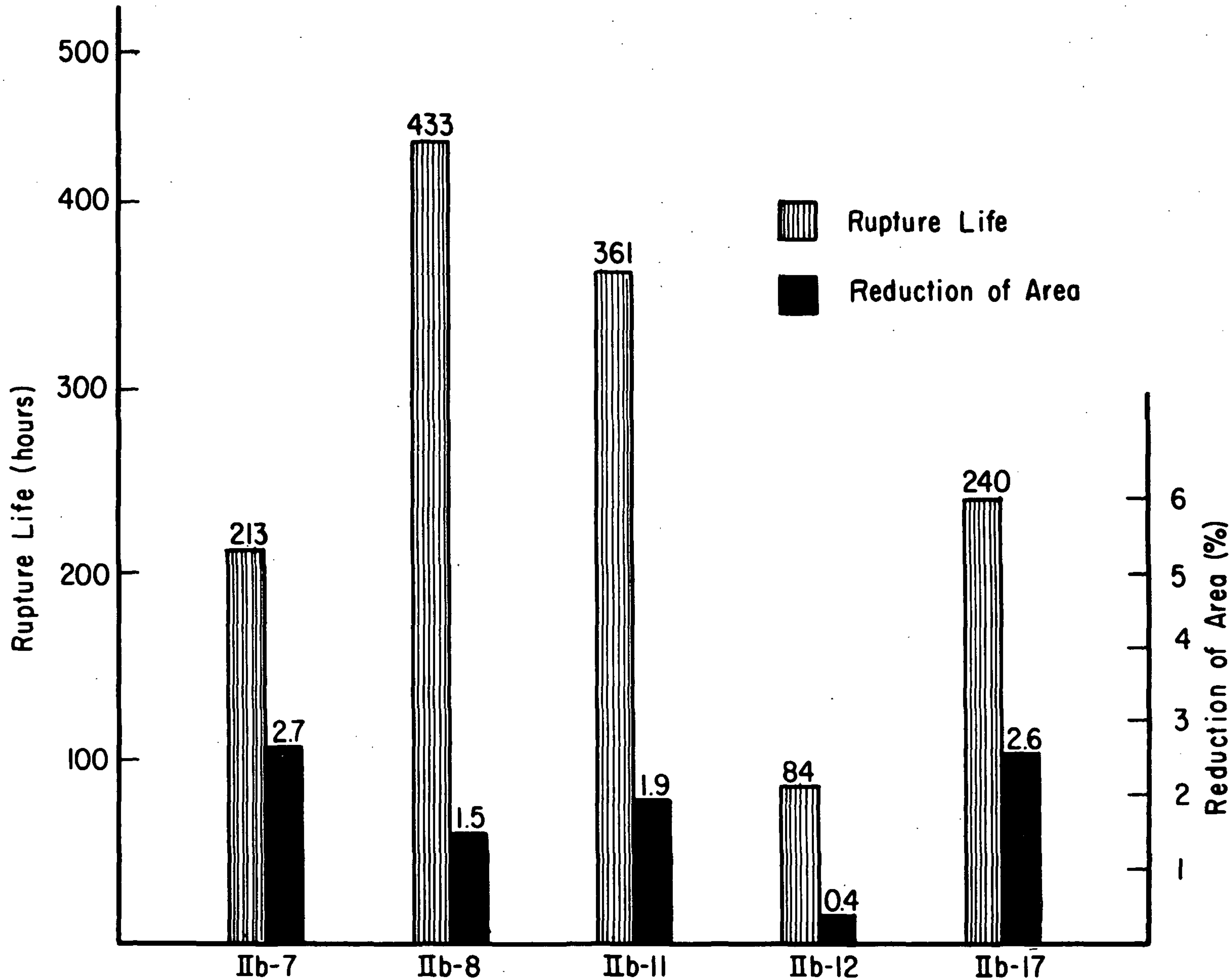


FIGURE 22 : 1400°F/90,000psi (760°C/621 MN/m²) STRESS RUPTURE PROPERTIES FOR FIVE BEST TASK I ALLOYS IN THE EXTRUDED CONDITION AND SUBJECTED TO A FULL SOLUTION HEAT TREATMENT.

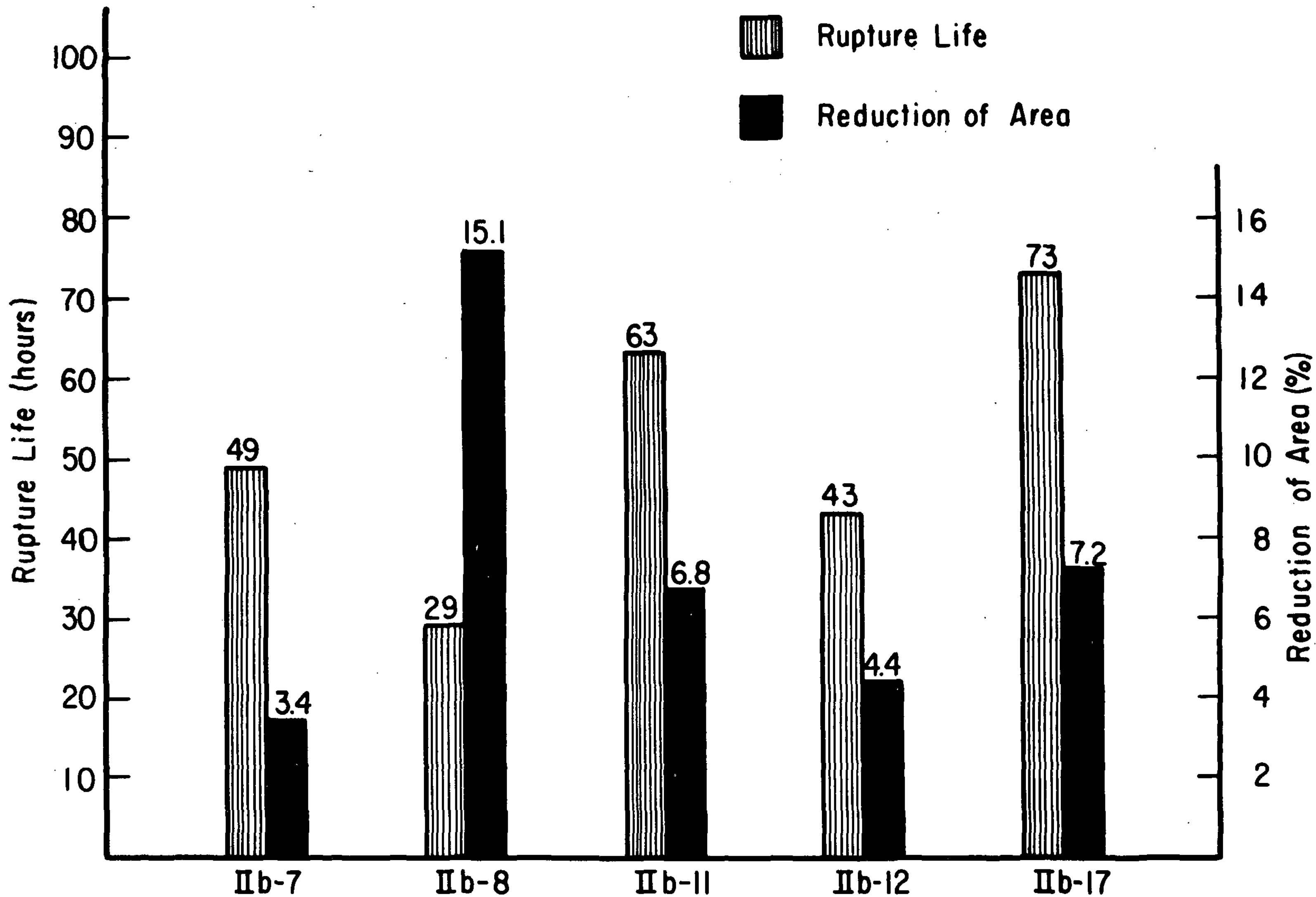


FIGURE 23 : 1800°F/25,000psi (982°C/172 MN/m^2) STRESS RUPTURE PROPERTIES FOR FIVE BEST TASK I ALLOYS IN THE EXTRUDED CONDITION AND SUBJECTED TO FULL SOLUTION HEAT TREATMENT.

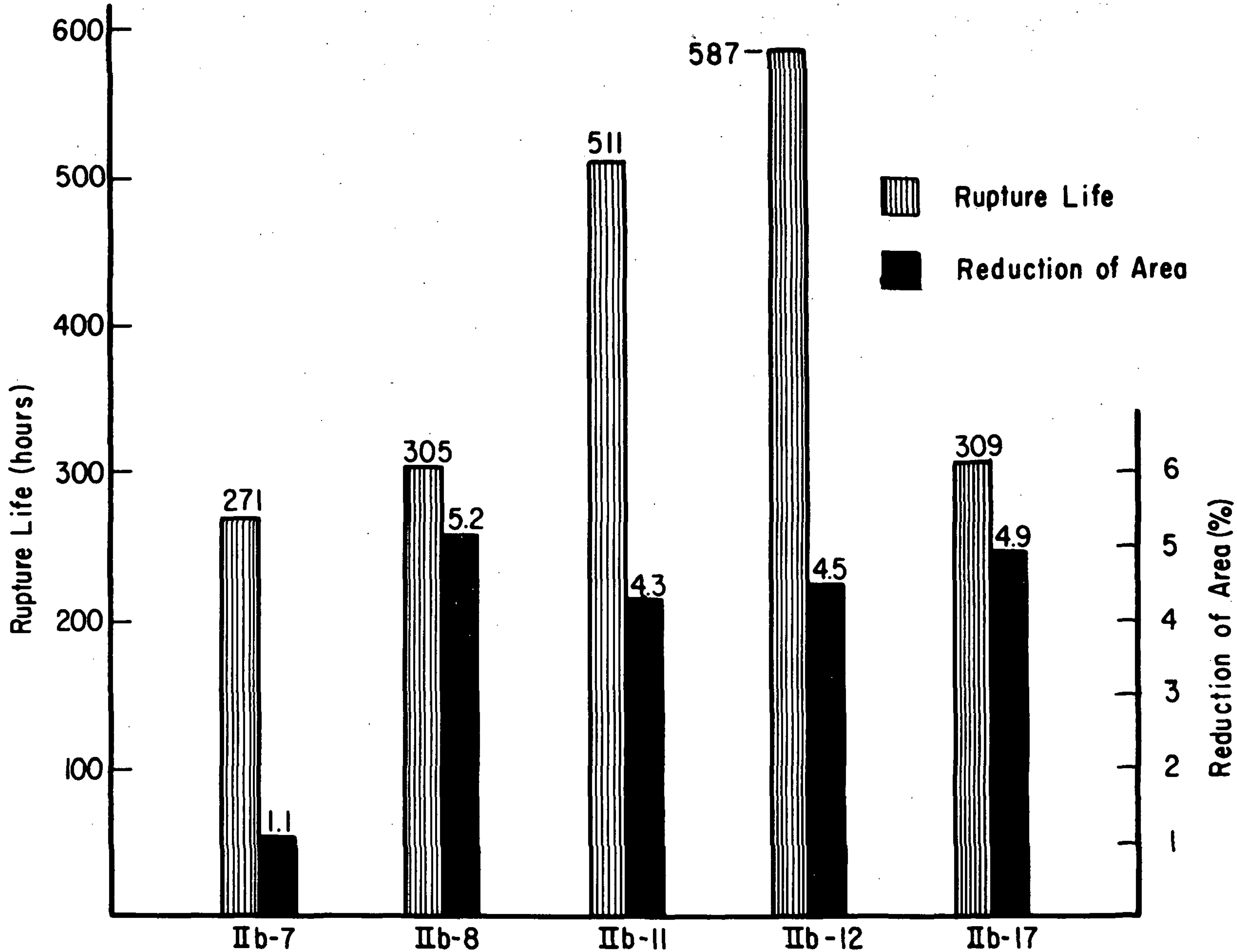


FIGURE 24: 1400°F/90,000 psi (760°C/621 MN/m^2) STRESS RUPTURE PROPERTIES FOR FIVE BEST TASK I ALLOYS IN THE EXTRUDED PLUS ROLLED CONDITION AND SUBJECTED TO A FULL SOLUTION HEAT TREATMENT.

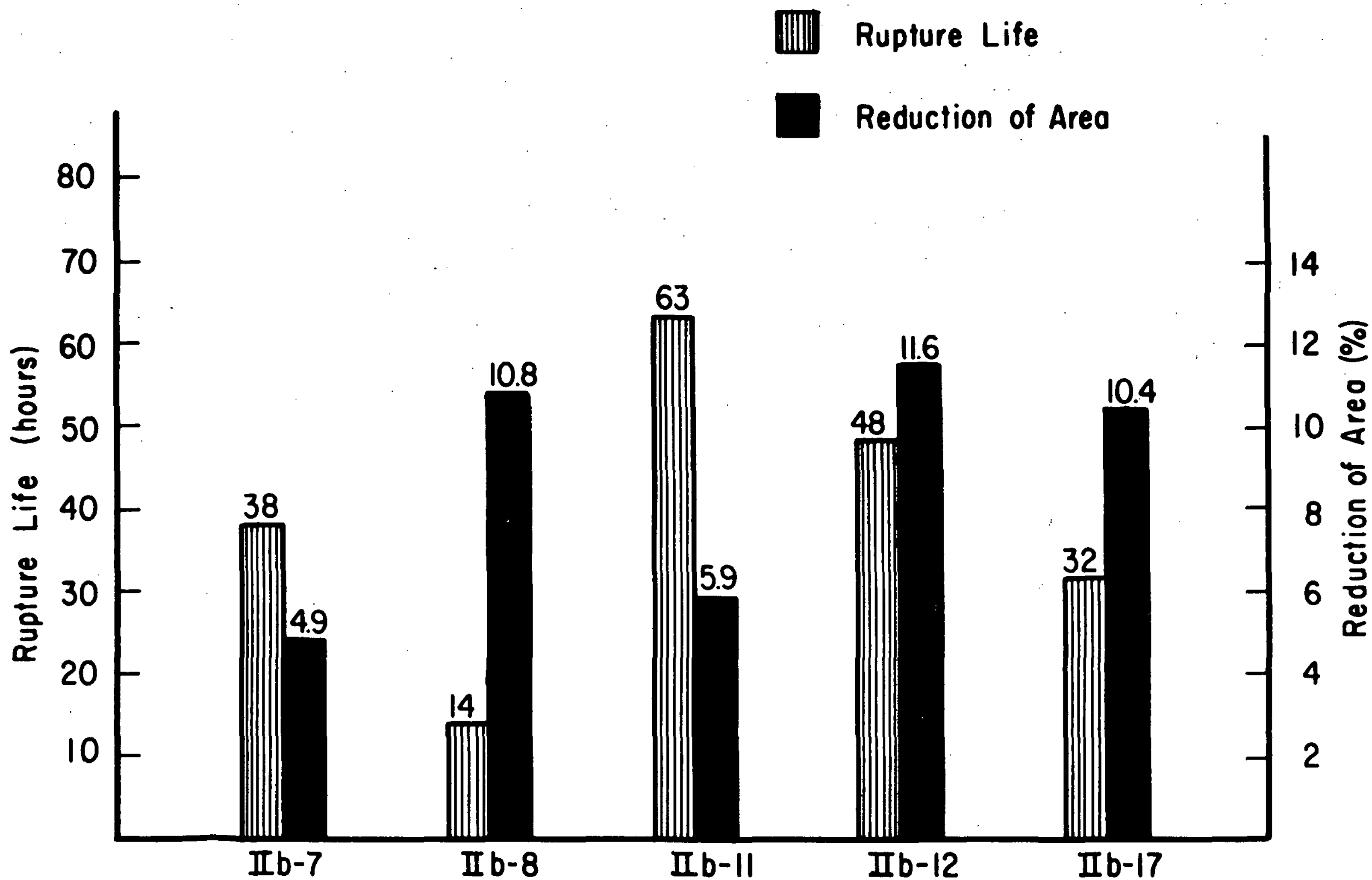


FIGURE 25 : 1800°F/25,000psi (982°C/172 MN/m^2) STRESS RUPTURE PROPERTIES FOR FIVE BEST TASK I ALLOYS IN THE EXTRUDED PLUS ROLLED CONDITION AND SUBJECTED TO A FULL SOLUTION HEAT TREATMENT.

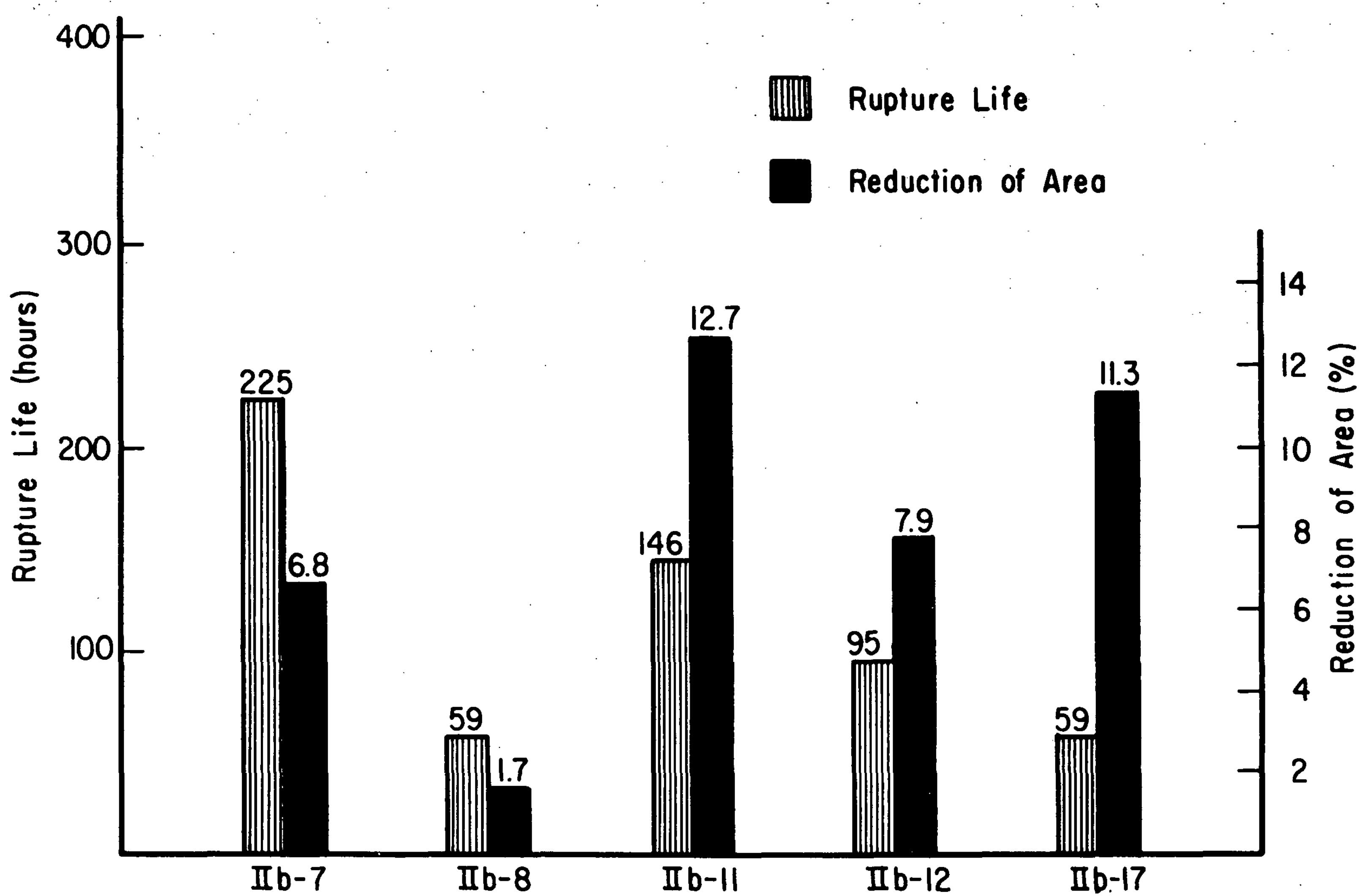


FIGURE 26: 1200°F/175,000psi (649°C/1207 MN/m^2) STRESS RUPTURE PROPERTIES FOR FIVE BEST TASK I ALLOYS IN THE EXTRUDED PLUS ROLLED CONDITION AND SUBJECTED TO A PARTIAL SOLUTION HEAT TREATMENT.

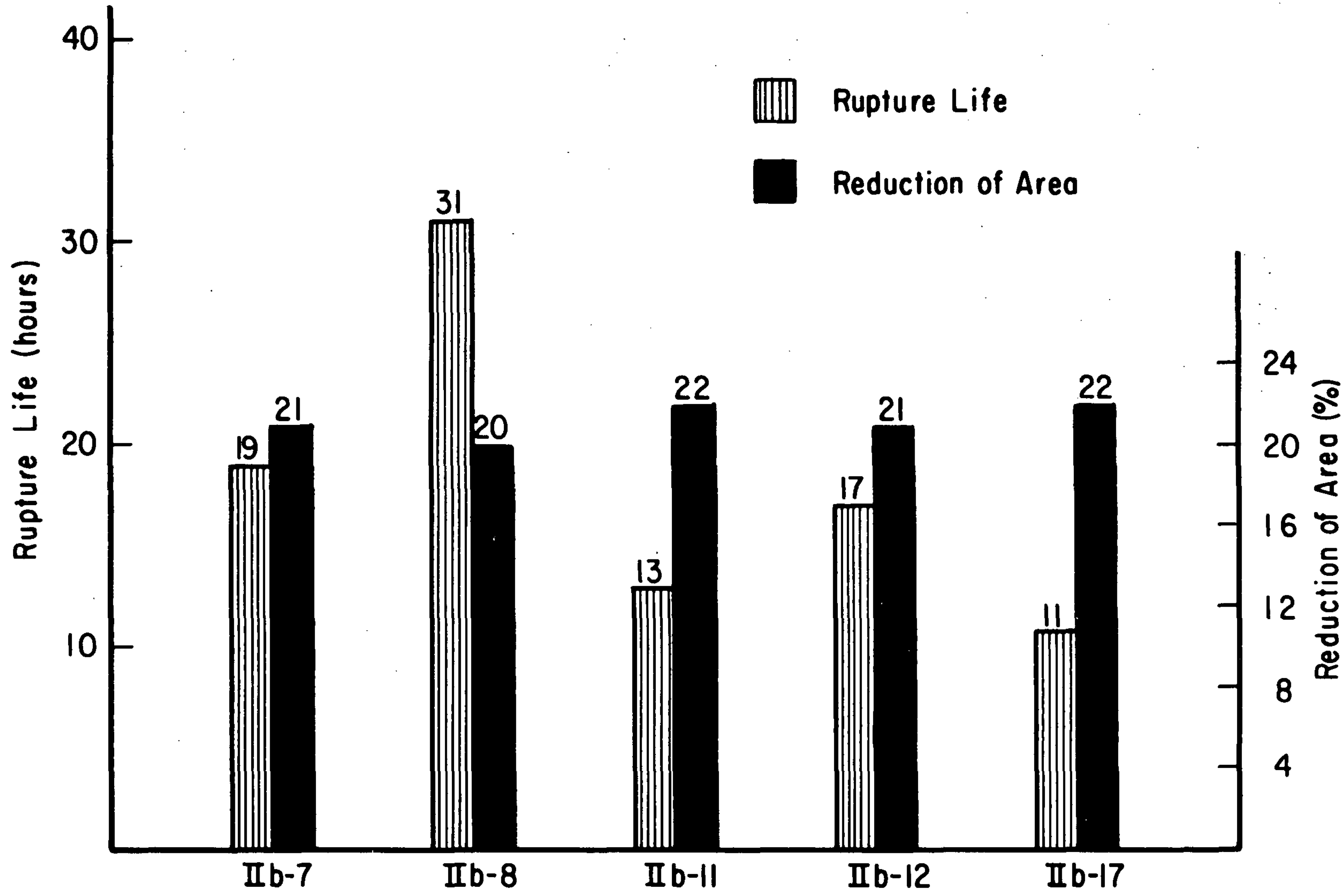


FIGURE 27 : 1400°F/90,000psi (760°C/621 MN/m^2) STRESS RUPTURE PROPERTIES FOR FIVE BEST TASK I ALLOYS IN THE EXTRUDED PLUS ROLLED CONDITION AND SUBJECTED TO A PARTIAL SOLUTION HEAT TREATMENT.

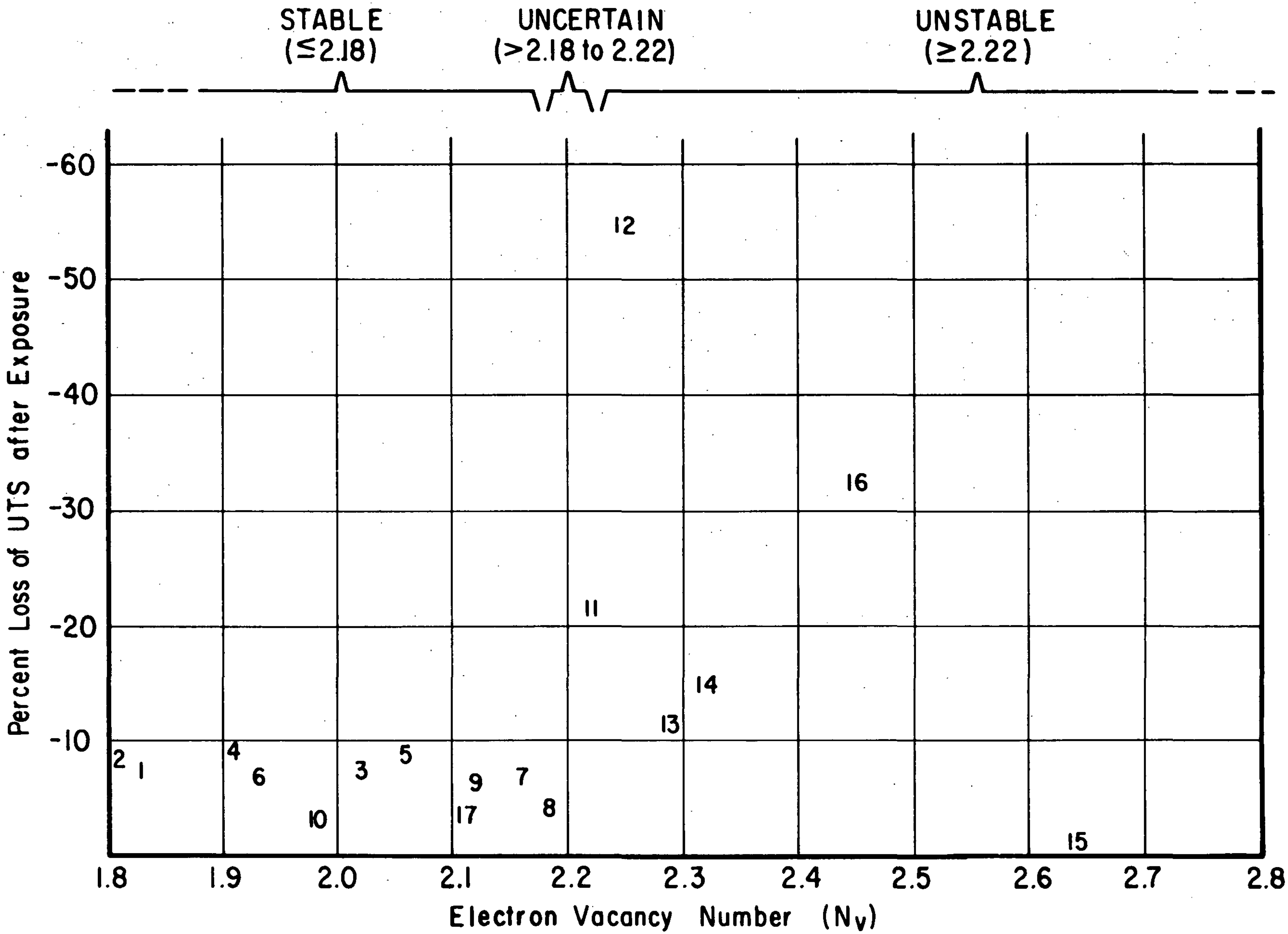
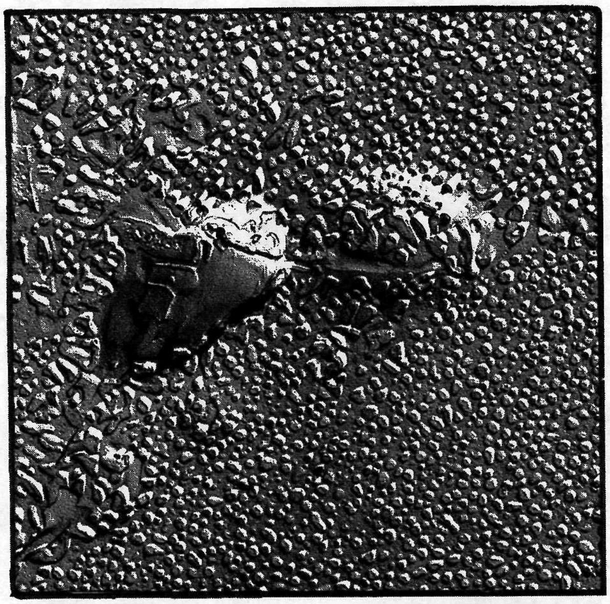
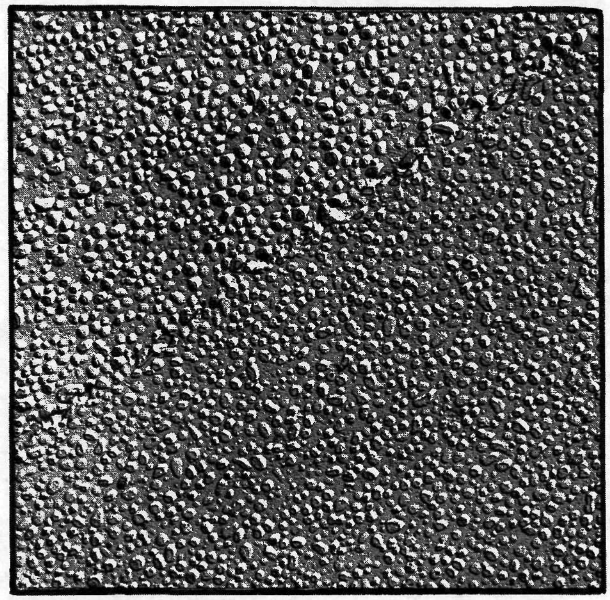


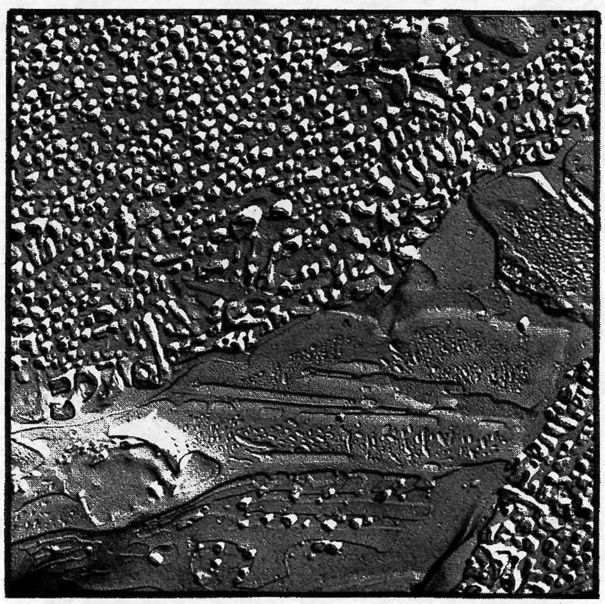
FIGURE 28: CHART ILLUSTRATING THERMAL STABILITY LIMITS WITHIN THE IIb ALLOY SYSTEM.



EM3461 5000X



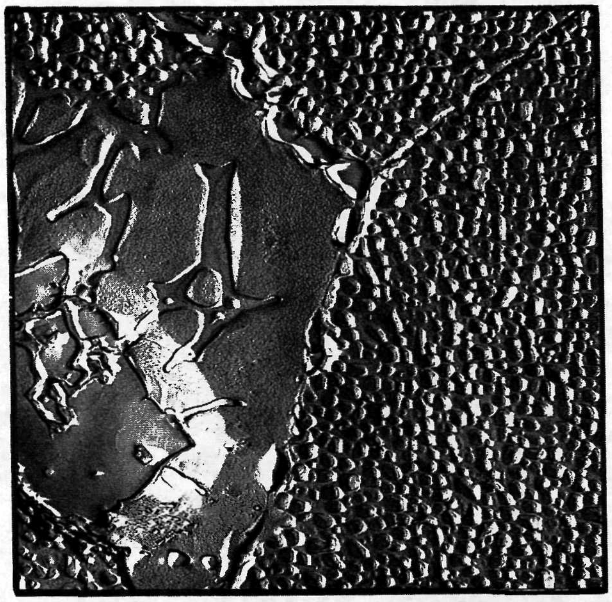
EM3459 5000X



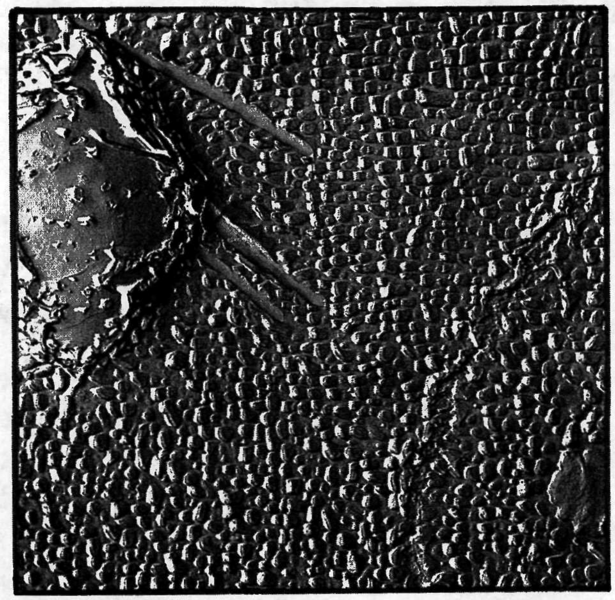
EM3458 5000X

FIGURE 29 : ELECTRON MICROGRAPHS ILLUSTRATING THE EFFECT OF 1500 HOURS EXPOSURE AT 1600°F (871°C) ON THE MICROSTRUCTURE OF IIb-7.

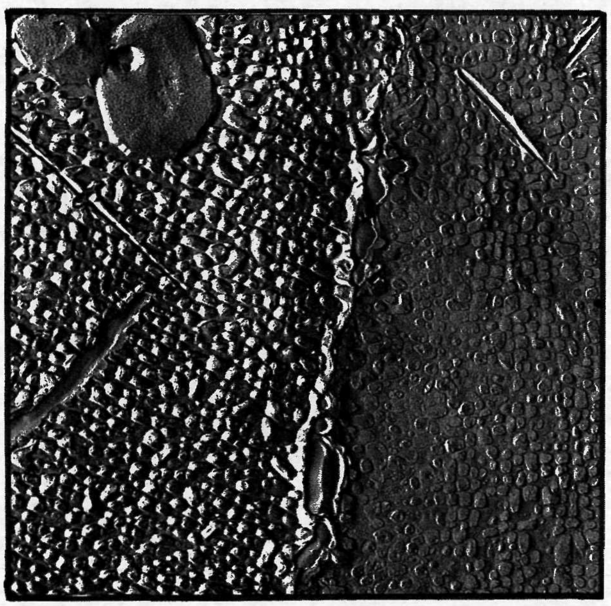
2250°F/2 hrs/RAC + 1600°F/16hrs/RAC + 1400°F/16hrs/AC
1232°C/ " / " + 871°C/ " / " + 760°C/ " / "



EM3466 5000X



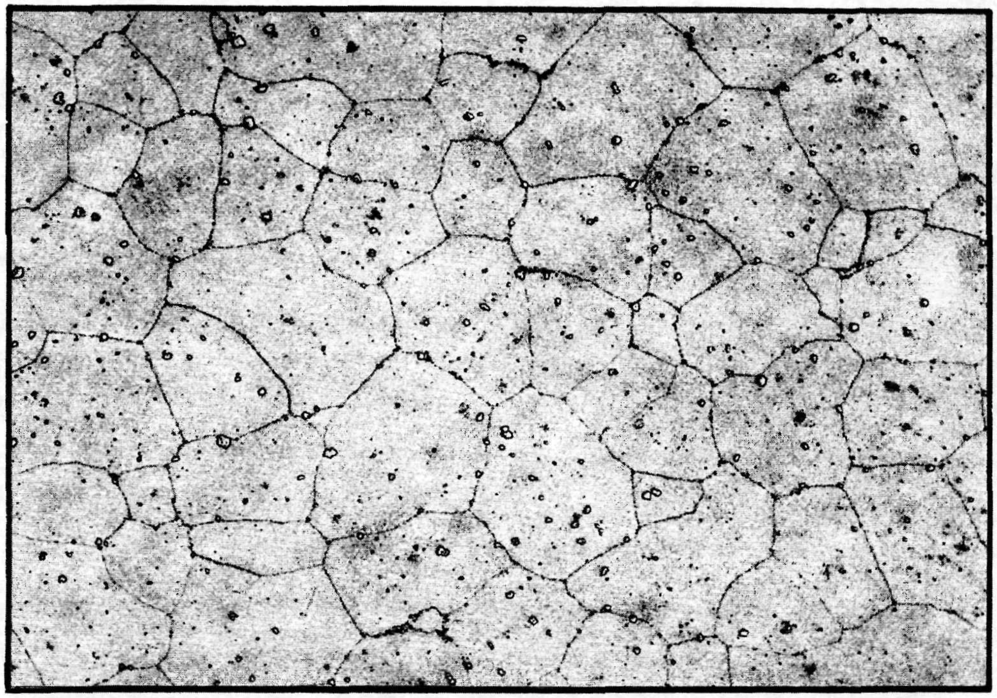
EM3462 5000X



EM3467 5000X

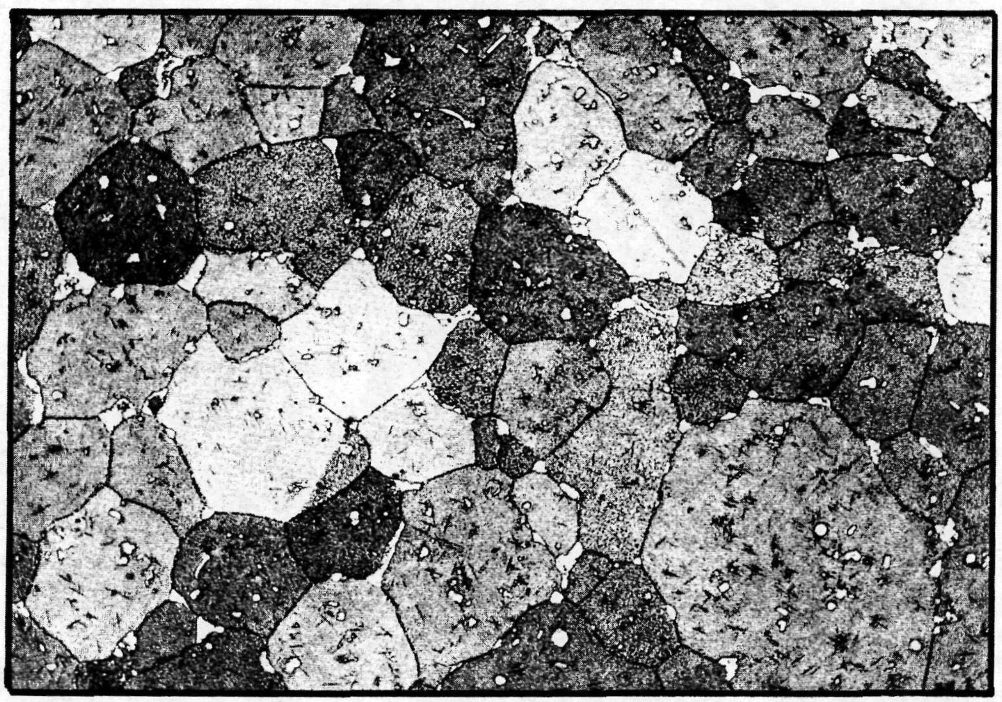
FIGURE 30: ELECTRON MICROGRAPHS ILLUSTRATING THE EFFECT OF 1500 HOURS EXPOSURE AT 1600°F (871°C) ON THE MICROSTRUCTURE OF IIb-11.

2250°F/2hrs/RAC + 1600°F/16hrs/RAC + 1400°F/16hrs/AC
1232°C/ " / " + 871°C/ " / " + 760°C/ " / "



R23926 200X

As-Heat Treated



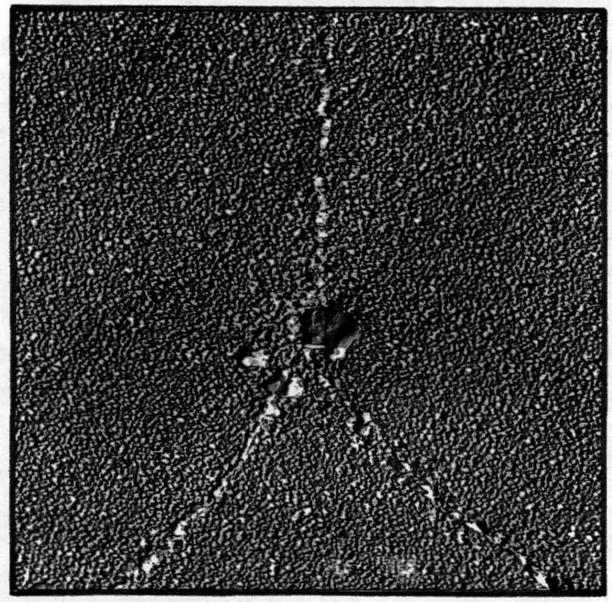
R23927 200X

As-Heat Treated + Exposed

FIGURE 31 : PHOTOMICROGRAPHS ILLUSTRATING THE EFFECT OF 1500 HOURS EXPOSURE AT 1600°F (871°C) ON THE MICROSTRUCTURE OF IIb-11.

2250°F/2hrs/RAC + 1600°F/16hrs/RAC + 1400°F/16hrs/AC
1232°C/ " / " + 871°C/ " / " + 760°C/ " / "

EM3579 5000X



EM3580 5000X

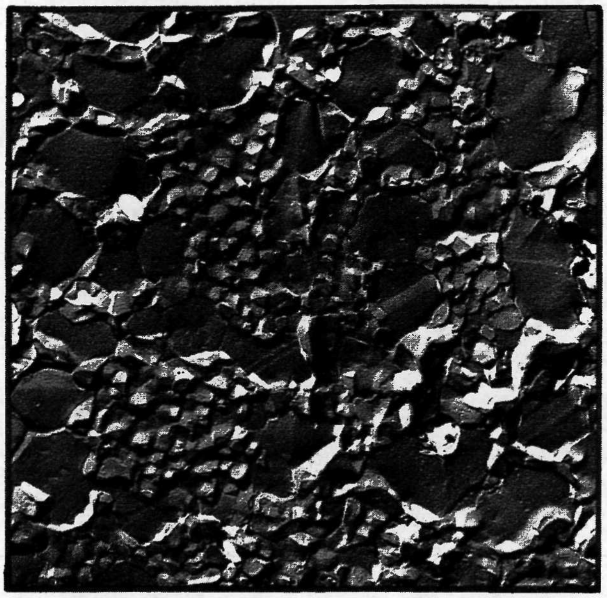
EM3583 5000X

FIGURE 32: ELECTRON MICROGRAPHS ILLUSTRATING THE STRUCTURE OF FULL SOLUTION HEAT TREATED IIb-H.

2225°F/2 hrs/RAC + 1650°F/16hrs/RAC + 1400°F/16hrs/AC
1219°C/ " / " + 899°C/ " / " + 760°C/ " / "

EM3586 5000X

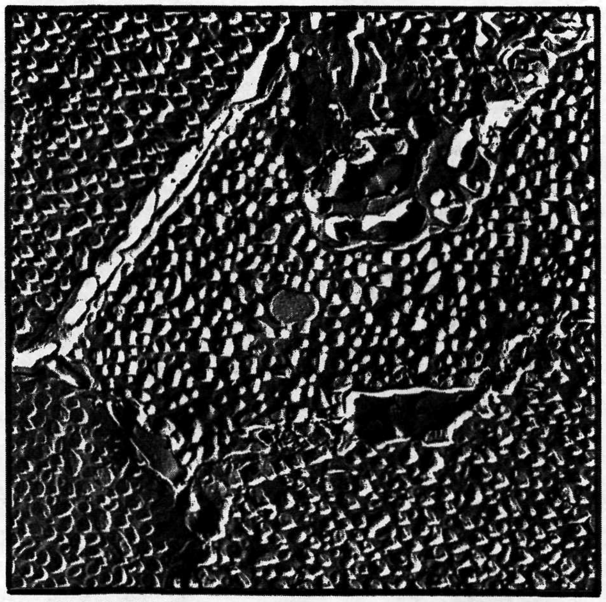
EM3587 5000X



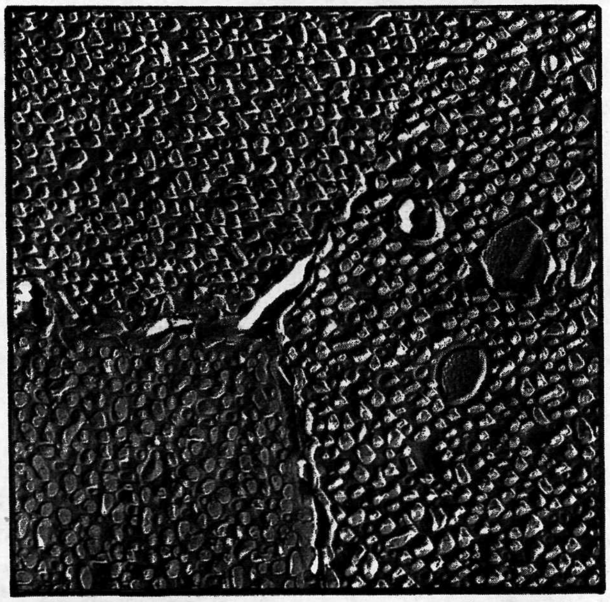
EM3588 5000X

FIGURE 33 : ELECTRON MICROGRAPHS ILLUSTRATING THE STRUCTURE OF PARTIAL SOLUTION HEAT TREATED IIb-L.

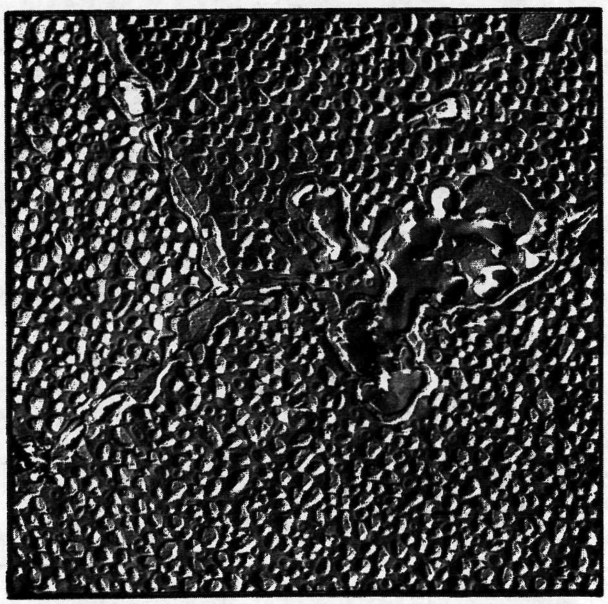
1600°F/16 hrs - increase to 2000°F/1 hr / OQ + 1400°F/16 hrs / AC
871°C/ " - " " 1093°C/ " / " + 760°C/ " / "



EM 3678 5000X



EM 3682 5000X

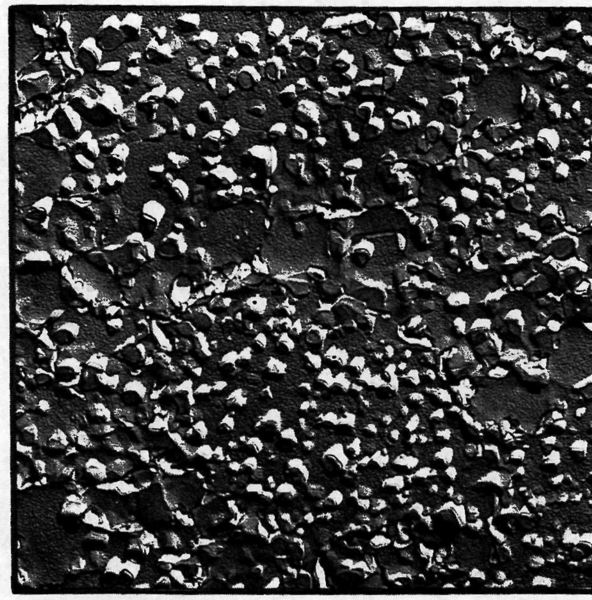


EM 3683 5000X

FIGURE 34: ELECTRON MICROGRAPHS ILLUSTRATING THE EFFECT OF 1500 HOURS EXPOSURE AT 1600°F (871°C) ON THE MICROSTRUCTURE OF IIb-H.

2225°F / 2 hrs / RAC + 1650°F / 16 hrs / RAC + 1400°F / 16 hrs / AC
1219°C / " / " + 899°C / " / " + 760°C / " / "

EM3670 5000X



EM3671 5000X

EM3672 5000X

FIGURE 35: ELECTRON MICROGRAPHS ILLUSTRATING THE EFFECT OF 1500 HOURS EXPOSURE AT 1300°F (704°C) ON THE MICROSTRUCTURE OF IIb-L.

1600°F/16 hrs - increase to 2000°F/1 hr/OQ + 1400°F/16 hrs/AC
871°C/ " - " " 1093°C/ " / " + 760°C/ " / "

APPENDIX A

Regression Analysis of Property Data

The seventeen alloys for which properties were determined in the first series of this program, form a statistically designed experiment. It is a 1/2 replicate of a 5 variable factorial set with each variable at two levels including a center point (1). This experiment permits the setting up of regression equations with a property of the alloy as the dependent variable equal to a constant B(o) plus the summation of the first order effects of the independent variables carbon, tungsten, tantalum, aluminum and hafnium, B(c), etc., and their two factor interactions, B(c•w), etc. The model regression equation is:

Property = B(o) + (B(c) x C) + (B(w) x W) + (B(ta) x Ta) +
(B(al x Al) + (B(hf) x Hf) + (B(c•w) x C x W) +
(B(c•al) x C x Al) + (B(c•hf) x C x Hf) + (B(w•ta) x W x Ta) +
(B(w•al) x W x Al) + (B(w•hf) x W x Hf) + (B(ta•al) x Ta x Al) +
(B(ta•hf) x Ta x Hf) + (B(al•hf) x Al x Hf)

which requires solving for the constant and 16 coefficients.

The solution of this equation was achieved by means of the computer program developed by S. M. Sidik and B. Henry (2). Coded values were assigned to the nominal content of the 5 variable elements in each of the 17 alloys, with the upper level being +1. design unit, the lower -1. design unit, and the center point 0. (see Tables I and II) Regression analyses were performed for the following properties.

1. On rolled alloys in the fully solutioned condition.

    a. At 70, 1400 and 1800°F (22, 760 and 980°C):

        Ultimate tensile strength
        Yield strength
        Tensile elongation
        Tensile reduction of area

    b. At 1400°F and 90,000 psi (760°C and 620 MN/m^2) and at 1800°F and 25,000 psi (980°C and 172.5 MN/m^2):

        Stress rupture life
        Elongation at rupture
        Reduction of area at rupture

2. On rolled alloys in the partially solutioned condition at 70, 1200 and 1400°F (22, 760 and 980°C):

Ultimate tensile strength
Yield strength
Tensile elongation
Tensile reduction of area

The computations were a series of iterations. In each iteration the constant, B(o), was re-evaluated and the coefficients with low probability of significance were eliminated and replaced by zero. The iterations were continued to the point where each of the coefficients remaining in the set would have a probability exceeding 90 percent. However, this set was not always chosen for calculating property predictions, since statistical significance and lowest estimated standard error for the estimated property did not always coincide. The sets selected were generally a compromise of these factors and can be found in Tables III, IV and V.

After the coefficients had been determined, predictions could be made for alloys within the general range of the 17 alloys already evaluated. It was felt that reliable predictions could only be obtained within 1.25 design units from the center point. Eleven levels were fixed and these were at -1.25, -1.00, -0.75, -0.50, -0.25, 0.00, 0.25, 0.50, 0.75, 1.00 and 1.25 design units. A simple computer program was written which fitted the design units into the regression equation for the coefficients which had been determined.

Since 11 levels of the design units were to be used and these applied to 5 elements of the composition, properties could be calculated for a total of 11^5 or 161,051 distinct compositions. Criteria were therefore established by which on the basis of one or two calculated property predictions, the computer would select for complete calculation only those compositions having properties of potential interest for further evaluation. For the alloys selected, a full set of property predictions would then be calculated from the regression equations. Critical property limits for compositions of alloys in the fully solutioned condition were a predicted 1400°F (760°C) stress rupture life in excess of 600 hours and a predicted room temperature reduction of area greater than 13.5%. Only 29 calculated compositions met these standards. For alloys in the partially solutioned condition, 31 alloys met the minimum criteria for predictions of 1200°F (650°C) yield strength of 225,000 psi (1550 MN/m^2) with 7.5% elongation, and 26 alloys (none of them included in the previous 31) exceeded a 1200°F (650°C) predicted yield strength of 230,000 psi (1585 MN/m^2).

The full set of property predictions was then used to select the two alloys which were to be evaluated in the final part of the program.

REFERENCES - APPENDIX A

1. Holms, Arthur G.: Designs of Experiments as Telescoping Sequences of Blocks for Optimum Seeking (As Intended for Alloy Development). NASA TN D-4100, 1967.

2. Sidik, Steven M.; and Henry, Bert: RAPIER, a Fortran IV Program for Multiple Linear Regression Analysis Providing Internally Evaluated Remodeling. NASA TND-5656, 1970.

TABLE IA

Coded Design Unit Values for Nominal Contents of Elements

Element	% Alloy Content	Value	% Alloy Content	Value	% Alloy Content	Value
Carbon	0.13	-1	0.19	0	0.25	+1
Tungsten	4.50	-1	6.00	0	7.50	+1
Tantalum	7.00	-1	8.50	0	10.00	+1
Aluminum	3.50	-1	4.00	0	4.50	+1
Hafnium	1.00	-1	1.75	0	2.50	+1

TABLE IIA

Series I Alloys with Elements Coded for Regression Analysis

Alloy No.	Carbon	Tungsten	Tantalum	Aluminum	Hafnium
1	-1	-1	-1	-1	-1
2	+1	-1	-1	-1	+1
3	-1	+1	-1	-1	+1
4	+1	+1	-1	-1	-1
5	-1	-1	+1	-1	+1
6	+1	-1	+1	-1	-1
7	-1	+1	+1	-1	-1
8	+1	+1	+1	-1	+1
9	-1	-1	-1	+1	+1
10	+1	-1	-1	+1	-1
11	-1	+1	-1	+1	-1
12	+1	+1	-1	+1	+1
13	-1	-1	+1	+1	-1
14	+1	-1	+1	+1	+1
15	-1	+1	+1	+1	+1
16	+1	+1	+1	+1	-1
17	0	0	0	0	0

TABLE IIIA

Regression Analysis Results for Tensile Properties of Alloys in Rolled and Fully Solutioned Condition

Coefficients	Room Temperature				1400°F (760°C)				1800°F (982°C)			
	UTS (psi)	YS (psi)	ELONG (%)	R.A. (%)	UTS (psi)	YS (psi)	ELONG (%)	R.A. (%)	UTS (psi)	YS (psi)	ELONG (%)	R.A. (%)
B(o)	203.140	162.256	9.797	11.560	169.394	145.449	4.788	7.346	61.871	53.815	2.144	2.524
B(c)	10.827	7.269	1.944	1.930	8.331	7.390	-0.497	-0.440	-0.500	-0.809	-0.053	-0.041
B(w)	-4.925	0.	-0.469	-0.647	3.644	-1.316	0.321	0.577	1.031	1.647	0.059	0.231
B(ta)	-7.155	-1.563	-2.393	-2.802	-5.787	-1.777	-0.366	-0.135	-2.469	-1.084	-0.059	-0.275
B(al)	-11.764	-2.837	-1.857	-1.830	-7.706	-0.509	0.859	0.627	-0.587	0.503	-0.759	-0.925
B(hf)	-10.944	-5.822	-1.981	-1.765	-11.106	-6.459	-0.566	-0.804	0.756	0.322	0.278	-0.012
B(c•w)	7.412	6.665	0.731	0.693	8.475	4.890	0.116	0.629	-2.200	-0.309	-0.391	0.087
B(c•ta)	4.945	5.950	-1.193	0.	5.656	5.879	0.566	0.579	1.275	1.634	-0.022	-0.281
B(c•al)	6.948	4.938	-0.219	0.	2.175	4.535	-0.009	0.454	2.519	-0.278	0.216	0.231
B(c•hf)	11.581	6.278	0.256	0.762	8.862	5.510	2.578	3.460	9.462	6.441	0.516	0.806
B(w•ta)	-10.231	-6.916	-1.319	-0.940	-11.019	-7.515	-1.166	-1.041	-4.231	-4.522	0.141	0.206
B(w•al)	-5.500	-4.497	-0.831	-0.381	-7.662	-2.746	0.259	0.441	-3.100	-2.159	-0.234	0.006
B(w•hf)	-4.942	-5.181	-0.518	-0.540	-8.062	-4.134	0.222	-0.048	-0.394	0.122	-0.059	-0.194
B(ta•al)	-6.895	-5.819	0.306	0.	-2.294	-5.110	-0.103	-0.141	-4.150	-3.666	0.009	-0.200
B(ta•hf)	-4.775	-4.953	1.144	0.890	-7.831	-7.622	-0.128	-0.610	-0.019	-1.334	0.219	0.110
B(al•hf)	-6.581	-5.647	0.394	0.	-2.187	-4.516	-0.428	0.027	-0.450	-0.072	-0.291	-0.400
Standard Error Estimate	6.766	2.868	3.848	1.612	22.079	9.918	2.135	3.560	8.770	4.916	0.928	1.552

TABLE IVA

Regression Analysis Results for Stress Rupture Properties of Alloys in Rolled and Fully Solutioned Condition

Coefficients	1400°F (760°C) and 90,000 psi (620 MN/m²)			1800°F (982°C) and 25,000 psi (172.5 MN/m²)		
	LIFE	ELONG (%)	R.A. (%)	LIFE	ELONG (%)	R.A. (%)
B(o)	189.092	2.419	3.940	21.761	5.874	8.187
B(c)	0.	0.716	0.889	-2.796	1.490	2.944
B(w)	50.512	-0.891	-0.621	6.771	-0.159	0.387
B(ta)	0.	0.698	-0.982	0.	0.090	-0.597
B(al)	66.978	-0.684	-0.459	6.110	-0.385	-0.422
B(hf)	17.615	-0.578	0.760	-4.129	-0.528	-1.426
B(c•w)	0.	-0.478	-0.561	0.	0.078	1.388
B(c•ta)	0.	0.960	-0.447	1.815	0.291	0.072
B(c•al)	21.072	-0.534	-0.661	3.571	0.741	1.259
B(c•hf)	147.685	0.	0.908	8.448	0.984	0.388
B(w•ta)	-86.763	-1.022	0.	-5.727	0.152	0.484
B(w•al)	-15.805	0.784	0.	3.967	0.728	0.759
B(w•hf)	0.	0.916	0.	-3.198	0.485	-0.007
B(ta•al)	-35.788	-0.578	0.466	-4.092	-0.259	0.618
B(ta•hf)	0.	-0.471	0.	-3.840	-0.416	-0.091
B(al•hf)	0.	0.772	0.658	-3.133	-0.591	-1.303
Standard Error Estimate	74.758	0.847	1.313	3.746	2.076	1.997

TABLE VA

Regression Analysis Results for Tensile Properties of Alloys in Rolled and Partially Solutioned Condition

Coefficients	Room Temperature				1200°F (560°C)				1400°F (760°C)			
	UTS (psi)	YS (psi)	ELONG (%)	R.A. (%)	UTS (psi)	YS (psi)	ELONG (%)	R.A. (%)	UTS (psi)	YS (psi)	ELONG (%)	R.A. (%)
B(o)	257.070	218.065	8.478	11.604	227.006	202.388	5.988	9.200	191.415	174.056	4.136	6.615
B(c)	-7.313	-3.806	0.	0.	-6.150	-3.312	-0.950	0.	-6.533	-2.006	-0.313	-0.896
B(w)	3.175	7.437	-0.859	-0.908	6.187	5.912	0.	-0.756	0.	2.040	-0.624	-1.179
B(ta)	0.	6.644	-1.554	-1.830	3.150	5.237	-0.550	0.	3.781	3.812	0.	0.
B(al)	-9.050	-2.861	-0.998	-1.274	-5.175	-0.812	0.	0.543	0.	-2.894	0.360	0.
B(hf)	-5.019	-2.231	-0.304	-0.655	-3.462	-2.975	-0.400	0.	2.565	0.	0.	-0.762
B(c•w)	0.	-2.426	0.	0.	0.	0.	0.487	0.	-2.071	-2.105	0.	-0.853
B(c•ta)	0.	0.	0.265	0.	0.	0.	0.	0.	0.	0.	0.	0.
B(c•al)	0.	0.	0.596	0.	0.	0.	-0.462	-0.769	0.	2.119	0.	0.629
B(c•hf)	2.931	0.807	0.	0.	0.	0.	-0.400	0.	4.355	2.910	0.	-0.688
B(w•ta)	0.	0.	-0.421	0.	0.	-1.275	-0.637	-0.456	0.	0.	0.	0.
B(w•al)	-2.400	0.	-0.352	-0.595	0.	0.375	0.	-0.669	0.	0.	0.	0.
B(w•hf)	-2.268	0.	-0.509	-0.701	-2.025	-1.887	0.	0.	2.583	0.	0.410	0.820
B(ta•al)	-3.619	-2.074	-0.448	0.	-2.425	-1.175	-0.837	-0.356	-4.869	-3.363	-0.662	-1.413
B(ta•hf)	0.	0.	0.	0.	0.	0.	-0.950	-0.544	-4.104	-2.270	-0.443	-1.297
B(al•hf)	2.193	3.088	0.	0.	3.912	3.462	0.	-0.481	-2.685	-3.585	0	0.
Standard Error Estimate	6.635	2.523	0.842	1.753	4.137	0.520	1.449	1.045	6.605	7.549	0.961	1.928

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