A HIGH PERFORMANCE AUSTENITIC ODS SUPERALLOY SHEET

FOR ADVANCED GAS TURBINE APPLICATIONS

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Abstract

Requirements for the next generation of advanced gas turbines dictate that sophisticated design concepts be combined with innovative materials and processing technologies in order that performance and durability goals can be satisfied. As gas stream temperatures for these designs can approach 2200°C (4000°F), hot section components will require higher performance materials than presently available. Despite the heavy investment being made in nontraditional materials that potentially require little or no cooling, it is clear that superalloy technology coupled with advanced cooling concepts will carry advanced gas turbine engine designs into the next century.

Experience has shown that cooling air requirements for Lamilloy®* combustor, turbine airfoil, afterburner liner, and nozzle components can be reduced as much as 50% relative to conventional film cooling technology. To provide the designer with the best possible sheet alloys for Lamilloy, work was initiated to identify superalloy alternatives to HA188 and MA956 that would offer a significant increase in performance while maintaining a balance of fabricability, strength, and oxidation resistance. As a consequence, MA754 austenitic oxide dispersion strengthened (ODS) superalloy sheet product feasibility programs were initiated with two ODS alloy producers, Inco Alloys International, Incorporated and PM Hochtemperatur-Metall, GmbH. Until this sheet development work was initiated, MA754 had not been available in sheet product form because of its very high temperature strength and attendant rolling difficulties.

This paper presents selected Allison Gas Turbine evaluation results for the sheet product form of MA754 and shows that while exhibiting excellent Lamilloy processing characteristics and promising forming characteristics, the MA754 ODS superalloy has the potential for being the world's strongest high temperature wrought sheet product.

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* Lamilloy is a registered trademark of General Motors Corporation.

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Introduction

Performance requirements for the next generation of advanced gas turbine engines have driven turbine inlet temperatures to near-stoichiometric levels. With gas stream temperatures for these designs approaching 2200°C (4000°F), hot section components such as combustors, turbine blades and vanes, and exhaust nozzles will require integration of sophisticated design concepts with innovative materials and processing technologies to satisfy performance and durability goals.

Despite the heavy investment being made in nontraditional materials that will require little or no cooling, superalloys coupled with advanced cooling concepts will carry advanced gas turbine engine designs into the next century. Because of this, Allison Gas Turbine has been active in the development of both advanced cooling concepts and advanced sheet alloys that are capable of higher temperature use.

Specifically, Allison has been working to develop processing technologies for a wide variety of hot section designs and components using the patented Lamilloy cooling concept. Lamilloy is a multilayered porous material designed for cooled airframe and propulsion system components (Figure 1). It features a labyrinth of holes and passages in a laminated assembly through which cooling air must pass before exiting on the liner gas path side. This unique configuration results in heat transfer efficiency levels far above the film cooling capability currently achieved in contemporary gas turbine engines. Lamilloy cooling configurations in combustor, turbine airfoil, nozzle, and exhaust liner applications have demonstrated that cooling air requirements can be reduced by as much 50% over conventional film cooling technology (Figure 2).

Advanced Lamilloy combustor, augmentor liner, and exhaust nozzle components have traditionally been fabricated from solid solution-strengthened sheet superalloys such as HAYNES** alloy No. 188 (HA188). However, because of strength limitations, metal temperatures have been limited to a range of approximately 870°C - 980°C (1600°F - 1800°F). More recently, significant and successful Lamilloy experience with nozzle and exhaust liner-type structures has been generated with the ferritic ODS

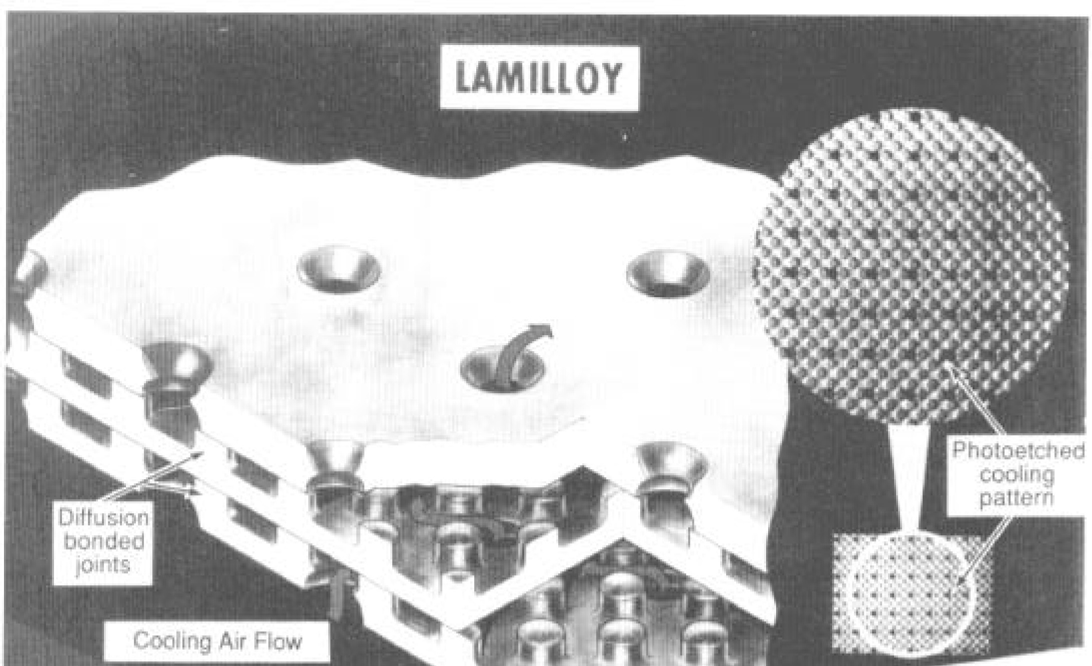

Figure 1. Cutaway view of typical Lamilloy sheet showing its laminated nature and multiple holes and passages that provide for very effective heat transfer when cooling air is circulated through the walls of the structure.

** HAYNES is a trademark of Haynes International, Incorporated

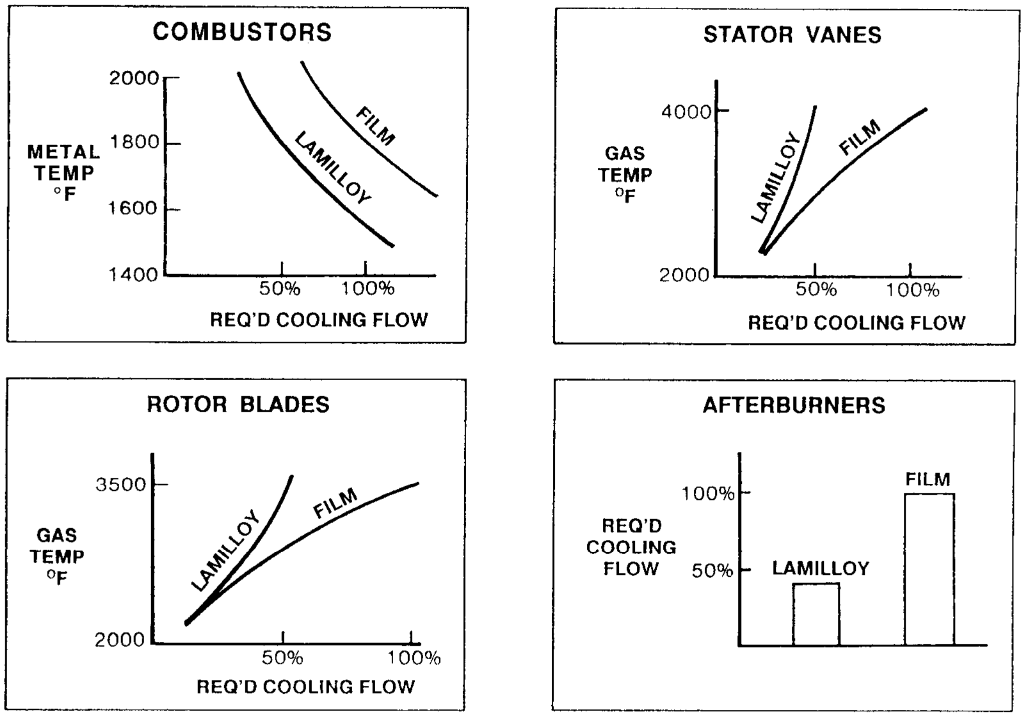

Figure 2. Lamilloy cooling effectiveness can reduce cooling air requirements in advanced gas turbine applications by 50% over conventional film cooling.

Incoloy† alloy MA956 in advanced military airframe and propulsion applications. Mechanically alloyed (MA) ODS materials derive high temperature strength primarily from a fine dispersion of insoluble refractory oxide particles achieved by the mechanical alloying process, which is described in Reference 1. MA956 sheet was attractive for these military applications as its very high temperature capabilities provided the opportunity to design cooled structures using minimal cooling air. However, use of MA956 created special challenges. In particular, the alloy is difficult to fabricate and although it offers outstanding oxidation characteristics up to 1200°C (2200°F) and beyond, the applications of interest were compromised by strength limitations.

To provide the designer with improved temperature capability sheet alloys for use in future Lamilloy applications, feasibility work was initiated at Allison to identify superalloy alternatives to HA188 and MA956 that would offer improved balance of fabricability, strength, and oxidation characteristics. With Allison's strong interest and background in ODS materials for advanced Lamilloy applications, it was decided to determine if Inconel†† alloy MA754 could be produced as high quality sheet that could be processed into Lamilloy product for next generation designs. MA754 is a mature nickel-chromium ODS alloy with an excellent military engine performance record in uncoated turbine vane applications; its nominal composition is given in Table I. Until this sheet development work was initiated, this alloy had not been available in sheet product form because of its very high temperature strength and attendant rolling difficulties.

Sheet Product Evaluations

In the late 1980s, Allison initiated austenitic ODS alloy sheet product feasibility programs with two ODS alloy producers, Inco Alloys International, Inc. (Inco) of Huntington, West Virginia, and PM Hochtemperatur-Metall, GmbH (PM) of Reutte, Austria. Both companies accepted the challenge to develop sheet manufacturing practices for conventional sheet and Lamilloy component applications.

† Incoloy is a registered trademark of the Inco family of companies.

†† Inconel is a registered trademark of the Inco family of companies.

Following substantial investment and effort, both Inco and PM produced MA754‡ sheet for Allison's evaluation. Attractive quality levels, mechanical properties, and processing characteristics were realized:

- sheet that satisfied Lamilloy quality standards was successfully produced in thicknesses of 0.25 to 1.27 mm (0.010 to 0.050 in.)
- excellent tensile and stress rupture properties to 1093°C (2000°F) were achieved
- compatibility with Lamilloy processing technology was verified
- promising sheet forming characteristics were demonstrated

Table I. Nominal Chemical Composition of Inconel Alloy MA754, Wt%

Nickel	Chromium	Carbon	Aluminum	Titanium	Yttrium Oxide (Y_2O_3)	Iron
78	20	0.05	0.3	0.5	0.6	1.0

Specific evaluation results presented in the following paragraphs indicate that MA754 sheet offers attractive processing characteristics along with high temperature (1093°C [2000°F]) strength superior to that of any other wrought superalloy sheet product.

Sheet Processing and Microstructure

Specific thermomechanical processing (TMP) routes for the MA754 sheet product are both company-specific and proprietary. In general, the sheet product is produced by hot rolling in one or two directions after powder consolidation by extrusion or HIP processing. Cold rolling and/or a variety of sheet polishing techniques may be utilized to meet various surface quality, thickness, and flatness requirements. A high temperature recrystallization annealing operation is utilized to produce a relatively coarse, pancake grain structure exhibiting good isotropy with respect to mechanical properties. Figure 3 depicts a typical microstructure for 0.51 mm (0.020 in.) thick MA754 sheet.

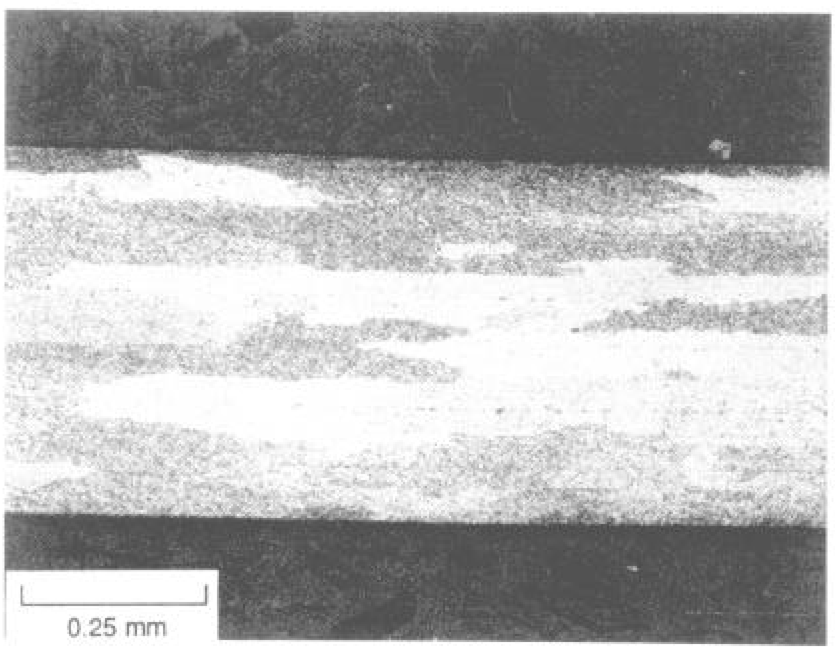

Figure 3. Representative microstructure of 0.51 mm (0.020 in.) thick MA754 sheet.

‡ MP designates its version of MA754 as PM1000. Both alloys have the same nominal composition (Table I). For clarity this paper will use MA754 when referring to product produced by either company.

Sheet Quality

Lamilloy manufacturing is accomplished through several processing routes depending on design requirements and the characteristics of the material to be fabricated. Lamilloy has been fabricated from a variety of sheet materials and from a wide variety of sheet quality levels. The quality of sheet available for Lamilloy processing determines the extent of additional material preparation required for compatibility with the process.

Through a schedule of sheet rolling and mechanical finishing operations, both suppliers were able to produce high quality MA754 sheet which was flat, uniform in thickness, and exhibited a good surface finish. Allison's previous experience with ODS sheet alloys has highlighted difficulties associated with producing ODS sheet in the 0.25 - 0.76 mm (0.010 - 0.030 in.) thickness range which meets Lamilloy requirements. It was therefore recognized that the successful production of this sheet product was a significant accomplishment. The composite quality level of sheet supplied by both sources is listed in Table II.

Table II. Sheet Quality Characteristics of MA754 Sheet

Maximum thickness range within a sheet	0.071 mm (0.0028 in.)
Flatness in 305 x 686 mm (12 x 27 in.) sheet (maximum out-of-plane)	6.4 mm (0.25 in.)
Sheet surface finish	2.5 - 3.0 RMS

Mechanical Properties

Representative tensile properties versus temperature curves for 0.51 mm (0.020 in.) MA754 sheet are depicted in Figure 4. Curves shown represent averages of longitudinal and transverse property data. In general, longitudinal and transverse strength levels agreed within 5 - 15%. At 1093°C (2000°F) the

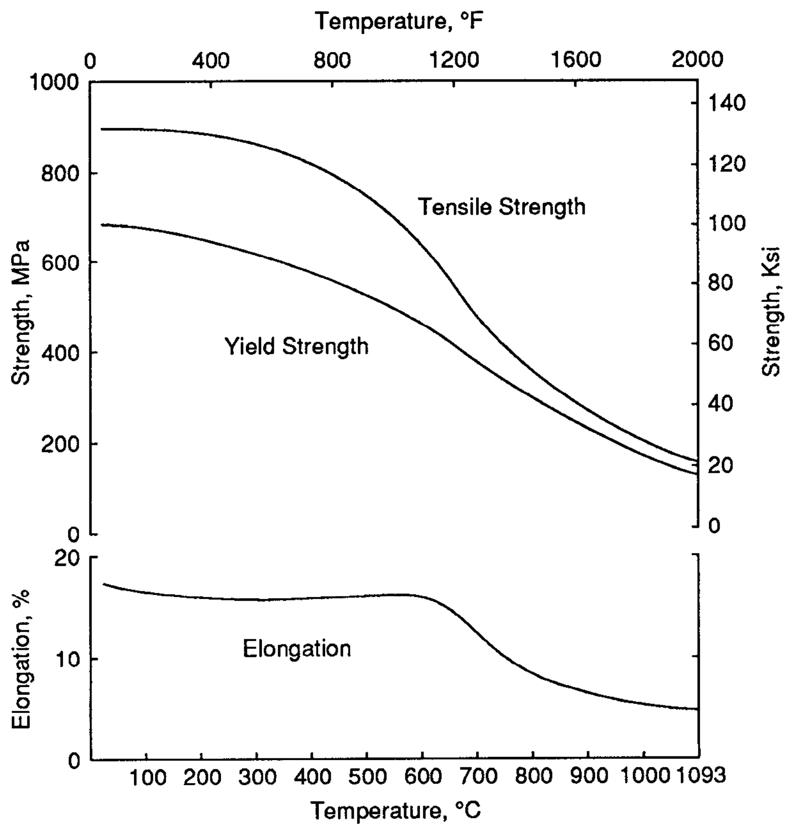

Figure 4. Representative tensile properties of 0.51 mm (0.020 in.) thick MA754 sheet.

MA754 sheet exhibited nearly twice the strength of comparable thickness ferritic ODS alloys (69 - 83 MPa, 10 - 12 ksi) while exhibiting superior ductility (4% versus 2%).

The outstanding stress rupture resistance of the 0.51 mm (0.020 in.) MA754 sheet is depicted in the Larson-Miller plot of Figure 5 along with comparable curves for alloys HA188 and MA956. When tested in its weaker direction, the MA754 sheet exhibited nearly twice the 200 hour stress rupture strength of MA956 at 1093°C (2000°F). Similarly, for a 1000 hour rupture life at 41.4 MPa (6.0 ksi), the MA754 sheet exhibited a 111°C (200°F) advantage over MA956 and a 194°C (350°F) advantage over HA188. The demonstrated 1093°C (2000°F) strength characteristics of the austenitic MA754 sheet are thought to be superior to those of any other wrought superalloy sheet.

Lamilloy Processing

Lamilloy is produced by photochemically machining an array of pedestals and holes in two or more layers of sheet material and subsequently diffusion bonding the layers into the laminated configuration shown in Figure 1. The pedestals can be produced by several photochemical machining processes. The response of the alloy to the chemical etchant is the major determinant in the selection of the appropriate process. In general, a new alloy must be able to meet the following requirements:

- chemical machining processes must achieve uniformly shaped pedestals
- processes must not produce detrimental chemical attack
- photochemical machining processes must be safe, environmentally manageable, and affordable
- the alloy must be compatible with diffusion bonding procedures

Photochemical machining of the MA754 sheet was successful as depicted in Figure 6. The etched surface is smooth with no evidence of detrimental chemical attack. Pedestals are uniformly shaped and meet engineering requirements for size control. The etching procedure for this alloy required only slight modification of our standard process and is considered to be environmentally safe and affordable.

Diffusion bonding was successfully achieved using standard Lamilloy techniques with minor changes to account for specific heat treatment requirements of this alloy. The bonded MA754 Lamilloy sheet

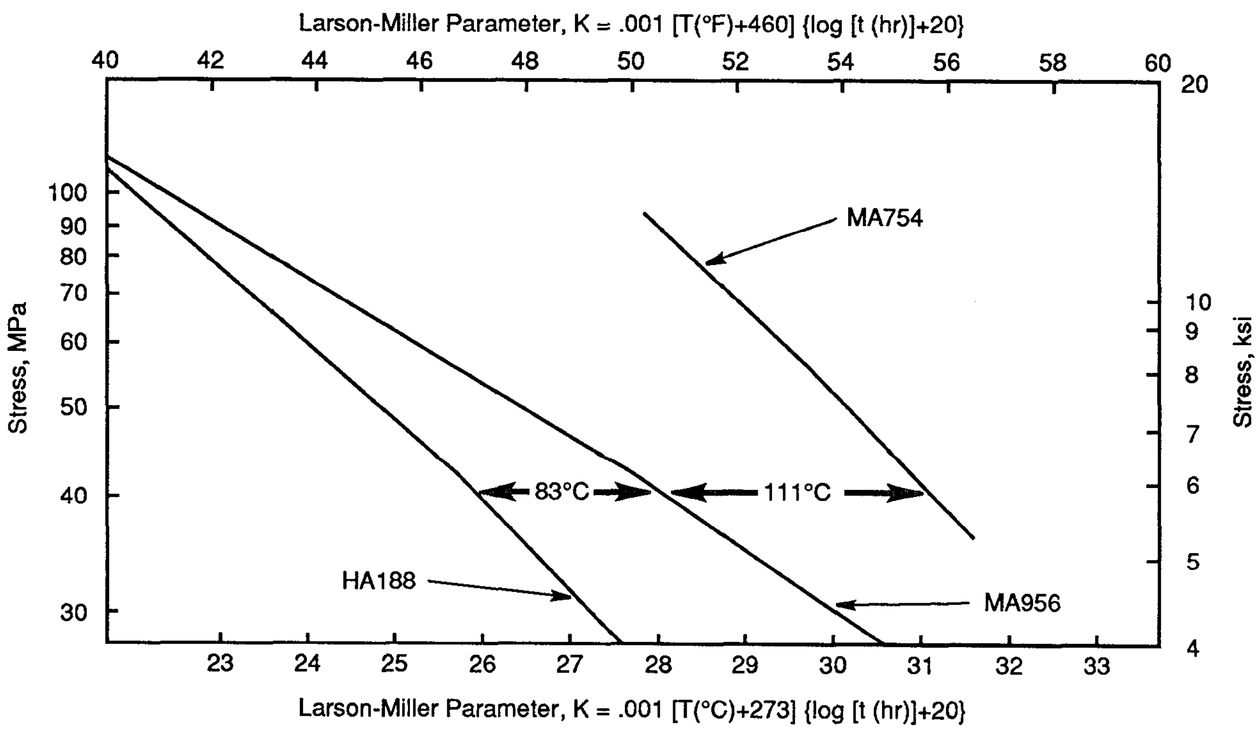

Figure 5. Stress rupture resistance of candidate high temperature sheet alloys highlighting the superiority of MA754 over both HA188 and MA956.

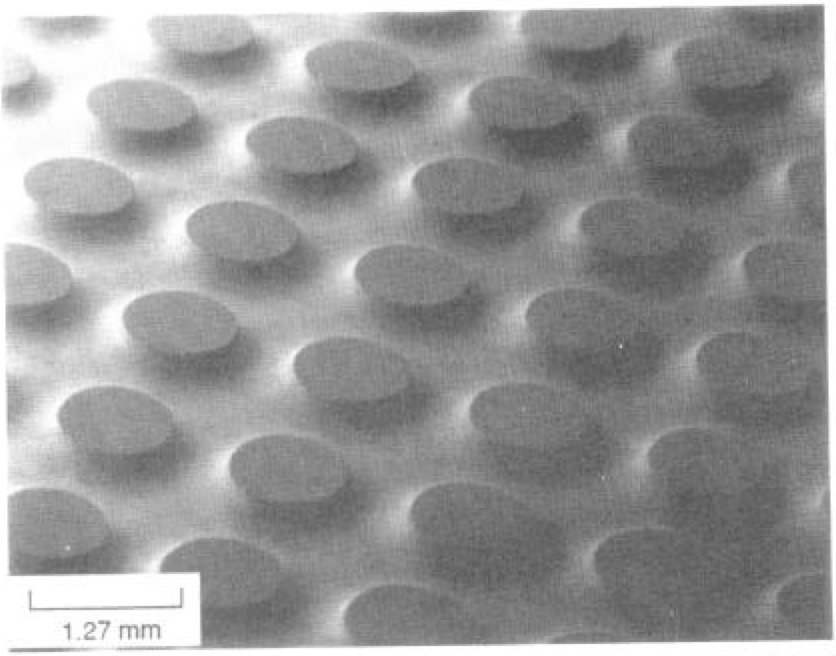

Figure 6. SEM photograph depicting an etched Lamilloy pedestal pattern in MA754 sheet.

met the traditional requirements of superalloy Lamilloy product. Bond coverage as measured by ultrasonic inspection was nearly 100%. Bond quality was verified by microexamination of the diffusion bond interface and peel testing. Figure 7 presents a summary of diffusion bond inspection results including ultrasonic inspection, metallographic examination, and peel test results. The MA754 sheet produced diffusion bonds with very low void content and met all requirements for Lamilloy bonding.

Forming Characteristics

An important fabrication characteristic of a new sheet product is its ability to be bent, drawn, and stretched into desired shapes. The forming limit diagram (FLD) is a sheet formability tool developed and used primarily in the automotive industry to quantitatively address sheet metal forming issues. The FLD is an empirical curve which identifies the biaxial strain states beyond which failure may occur in sheet metal forming. In an FLD, strain in components or specimens formed to the onset of failure is presented in terms of major and minor strains measured from deformed circle grids printed on the forming blanks or specimens prior to deformation. Reference 2 provides an excellent introduction to the use of FLDs.

Allison developed a working FLD for 1.0 mm (0.040 in.) MA754 sheet to assess the potential of utilizing existing tooling to form a representative combustor transition section detail. The FLD depicted in Figure 8 correctly suggested that the detail could not likely be formed in one operation, but successfully predicted the stage of die closure at which the detail should be removed and annealed before further forming was attempted. This use of the FLD led to successful forming of the detail blank shown in Figure 9. The MA754 sheet exhibited promising formability, and it is anticipated that a similar approach to forming Lamilloy details will be successful.

Future Directions

Work completed to date has demonstrated that the potential exists for significantly upgrading the temperature capabilities of sheet metal structures in modern gas turbine hot section design. It is projected that by combining these enhanced metal operating temperature capabilities with innovative fabrication techniques and advanced cooling concepts, improved performance characteristics for a variety of combustor, nozzle liner, and afterburner applications will be realized.

Additional process development work is required for this potential to be realized. Specifically, the supplier base needs to continue its process development work aimed at producing a consistent, affordable product. This should include work in the areas of powder manufacture, powder consolidation,

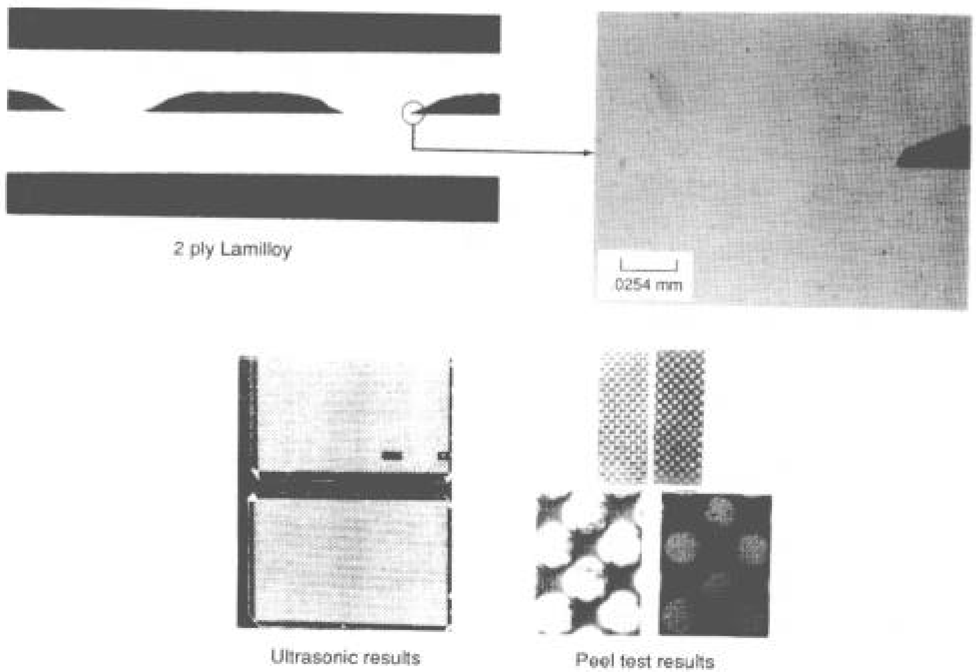

Figure 7. MA754 sheet exhibited excellent Lamilloy diffusion bonding characteristics (microstructure unetched).

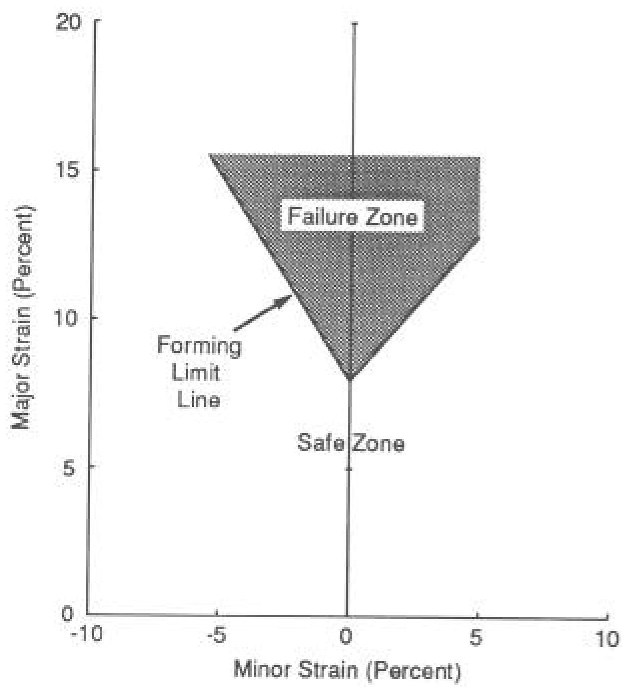

Figure 8. Forming limit diagram for 1.0 mm (0.040 in.) MA754 sheet was used to successfully assess formability of a representative combustor component detail.

hot/cold work rolling practices, and postrolling thermal treatment. The database for MA754 sheet product also needs to be expanded to provide the statistically reliable information required by the designer. From a Lamilloy component fabrication viewpoint, forming, etching, and joining practices need to be more fully optimized. Finally, for selected applications, compositional modifications should be considered and evaluated in order to extend oxidation capabilities beyond those currently defined for MA754.

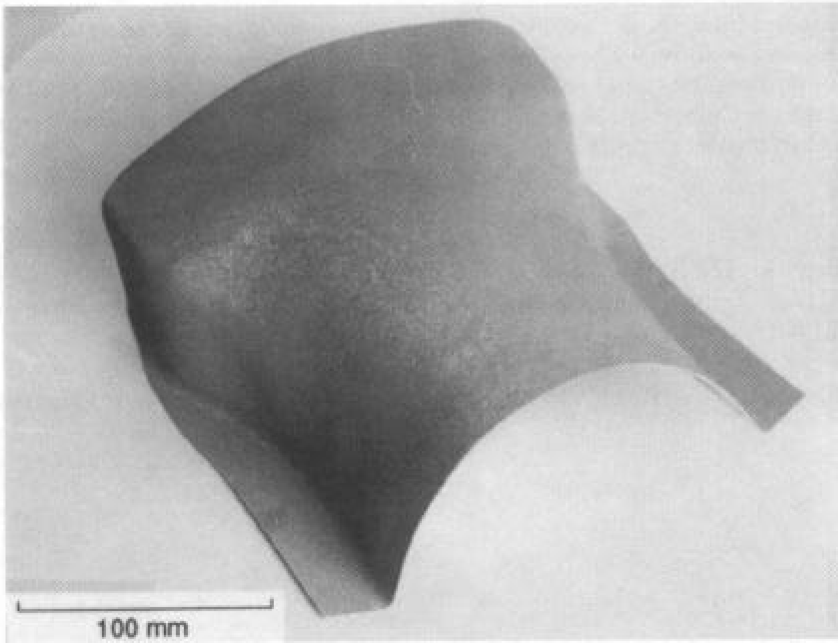

Figure 9. MA754 sheet exhibited promising formability as illustrated by this combustor transition section detail (untrimmed).

Overall, the prognosis for advanced austenitic ODS sheet products in advanced hot section applications is highly encouraging. These superalloy products will be ideally suited for applications requiring a balance of formability, strength, and high temperature environmental characteristics that is significantly beyond that available today.

Concluding Remarks

Today's emphasis in high temperature materials development is heavily focused on advanced high risk materials systems that are sought to achieve propulsion goals associated with programs such as NASA's High Speed Civil Transport (HSCT) and the DOD's Integrated High Performance Turbine Engine Technology (IHPTET) initiative. These high risk materials systems are often referred to as revolutionary materials and include ceramics, ceramic composites, intermetallics, and intermetallic composites. These systems offer the potential for attractive high temperature strength capabilities, low density, and excellent environmental resistance. However, these high temperature materials will not become viable until a number of significant issues involving joining, ductility, toughness, stability, repeatability, cost, and producibility are resolved.

Despite these issues, work should and will continue to develop these revolutionary materials, as the potential payoffs cannot be ignored. However, the support committed to revolutionary materials needs to be balanced with that required to support evolutionary materials such as superalloy MA754 sheet product. As has been described, significant performance benefits are potentially available from the evolutionary development of superalloys as well as other conventional materials systems. The focus of efforts should be on the technologies needed to make these conventional materials stronger as well as more affordable, forgiving, and reliable. With this approach, significant performance enhancement for propulsion systems is likely to be realized. By utilizing evolutionary materials in combination with innovative design concepts such as those represented by Lamilloy, vigorous competitive advancements in propulsion technology can and will be achieved while researchers work the many significant challenges unique to revolutionary materials.

Acknowledgments

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