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Volume 621

Manufacturing Applications of Lasers

Peter K. Cheo

Chairman/Editor

Presented in cooperation with

American Association of Physicists in Medicine • Center for Applied Optics/University of Alabama in Huntsville
Center for Laser Studies/University of Southern California • Georgia Institute of Technology
Institute of Optics/University of Rochester • Laser Association of America
Office of Naval Research • Optical Sciences Center/University of Arizona

23-24 January 1986
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MANUFACTURING APPLICATIONS OF LASERS

Volume 621

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MANUFACTURING APPLICATIONS OF LASERS

Volume 621

INTRODUCTION

The proceedings contain papers presented at the SPIE conference on Manufacturing Applications of Lasers, held 23–24 January 1986, in Los Angeles, California. The purpose of this meeting was to bring together laser experts and users in several key manufacturing areas of industrial laser applications. Many laser systems described in this meeting are either at or near the stage for use on production lines by aerospace, automotive, microelectronics, and power utility industries.

I wish to express my sincere appreciation to Gary Whitney, Susan Allen, and Dean Hodges for their efforts in helping me to organize this program. Their participation ensures the proper coverage of the key laser application areas and has made this meeting most successful.

Peter K. Cheo
United Technologies Research Center

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LASER WELDING OF CYLINDERS

Rob Kraencke and Victor Gregson
Laser Center
Westinghouse Marine Division
401 E Hendy Avenue P O Box 3499
Sunnyvale, California 94088-3499

Introduction

High-power lasers (greater than 5 kW) have been in existence for about two decades However, their use by industry is extremely limited. Numerous researchers have demonstrated laser welding to a thickness of nearly 1 inch But almost all laser welding today is for a thickness of 1/8 inch or less The welding discussed here is for material thickness greater than 1/4 inch in a shop setting for which small number job lots are common

Laser welding was investigated at the Westinghouse Marine Division as a process to reduce the cost of welding cylindrical fabrications These cylinders are now fabricated in various sizes, thicknesses, and materials by using a variety of conventional welding processes The thickness range of the cylinders considered for laser welding had a range of 0 312 to 0 625 inch The materials used to fabricate these cylinders are carbon steel, 300 series stainless steel, and 17-4 ph stainless steel

The majority of the cylinders requires melt-through type, full-penetration welds After welding, all cylinders are visually inspected by either liquid penetrant or by the magnetic particle technique In some cases, radiographic inspection is required

Shop Processing

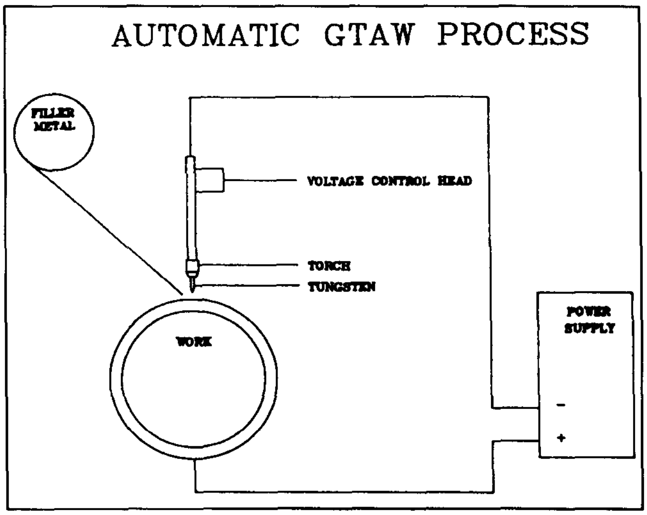
Laser welding is treated the same as any other welding process in that it must meet a number of quality control and customer requirements. First, drawings must be revised to indicate laser welding and which joint designs are modified Second, weld parameters of laser power, speed, focal placement, etc are determined experimentally These parameters must be able to accommodate slight variations in thickness and fit-up

Third, all welding must be done to a code or standard which, in this case, is MIL-STD-278. A procedure qualification is welded, as required, using the previously determined parameters In this case, MIL-STD-248 was used to determine the extent of destructive and nondestructive testing required A process specification, which describes how production welding shall be done, is generated from the parameters used to weld the qualification test plate Essential variables of a laser welding specification have been defined in a 1984 ASME Section 3 code case

Last, operators must be certified to verify their ability to produce sound welds Such certification is done internally in each business enterprise (sometimes with qualified third parties, as well) For this, the welder uses test plates and the specification to make a test weld If it meets the requirements, the welder is certified to weld that material and thickness

Present Welding Method

Cylinders with melt-through requirements are generally fabricated using the Gas Tungsten Arc Welding (GTAW) process (Figure 1), by itself or in combination with another welding process The process uses a variety of joint designs which are often machined to "U" grooves (Figure 7). Filler metal may or may not be used to weld the root pass Since GTAW is very slow, other processes are sometimes used to fill the joint after completing several layers with GTAW



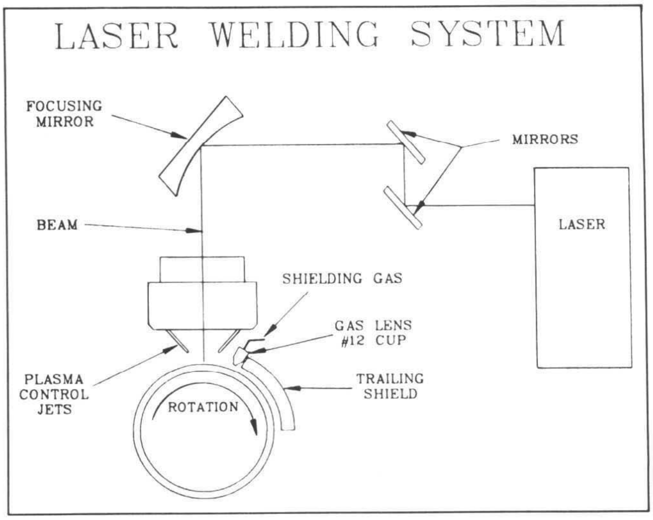
1 The Gas Tungsten Arc Welding Process

The advantages of the GTAW process (Figure 2) are that it consistently produces high quality welds; the equipment is comparatively inexpensive; spare equipment is readily available, and there is experience with the process. Also, when used manually, the process is tolerant of joint mismatch, excessive root openings, and out-of-round parts

The disadvantages of the process (Figure 2) are slow travel speeds and a low deposition rate which produce a significant amount of distortion

GTAW PROCESS	
ADVANTAGES	-TOLERANT OF OUT OF ROUND PARTS -TOLERANT OF ROOT OPENINGS -LOW COST EQUIPMENT -ALTERNATE EQUIPMENT AVAILABLE -EXPERIENCE WITH PROCESS
DISADVANTAGES	-SLOW PRODUCTION RATE -HIGH OVERALL HEAT INPUT -DISTORTION

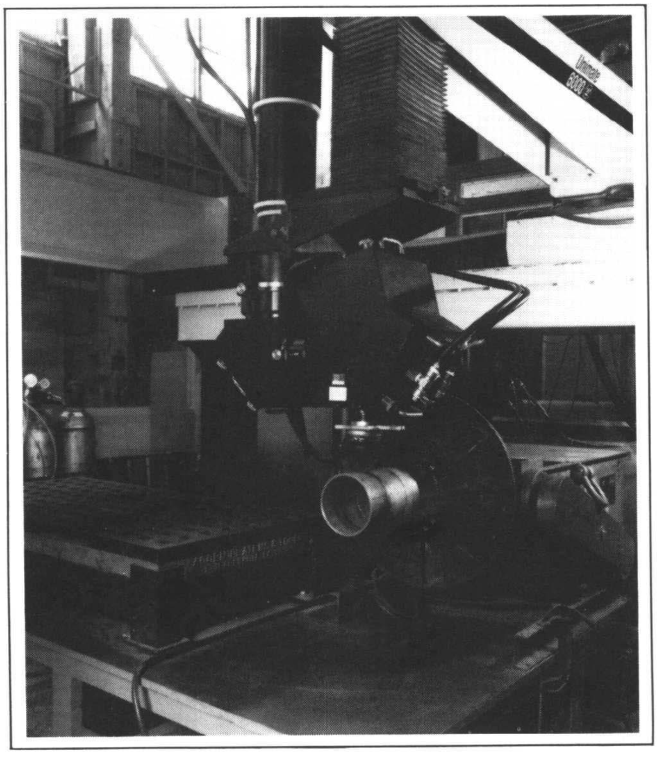
2 Advantages and Disadvantages of the Gas Tungsten Arc Welding Process



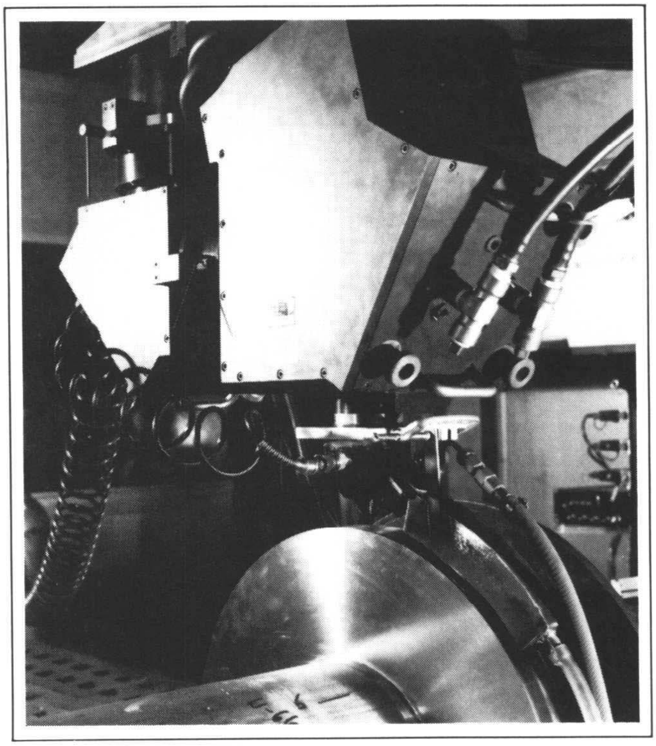
3. The Laser Welding Process

Laser Welding

Laser welding has the ability to produce full-penetration, single-pass welds at high travel speeds in comparison to the Gas Tungsten Arc Welding process. Figure 3 illustrates the general approach which is used. Figure 4 is a photograph of the laser welding head. Figure 5 shows details of the gas shielding apparatus. Mirrors direct the beam to the final focus mirror. Most laser welding is done in the down-hand direction unless circumstances dictate otherwise. To date, the vast experience of most laser welders is to process the parts using an autogenous weld. This, in turn, requires close and accurate joint fit-up. Wire feed,



4. Photograph of the Laser Weld Head



5. Photograph of Gas Shielding Apparatus

together with laser, is possible, and some groups are gaining experience but autogenous welds dominate.

The advantages of laser welding are listed in Figure 6. High production rates result from a ten-fold increase in speed from GTAW to Laser. This is compounded by the fact that laser welding is a single-pass process; whereas, GTAW is often a multipass process. The single-pass, autogenous weld process is similar to the electron-beam keyhole process. This produces a laser weld bead which is narrower than GTAW beads and which has a higher aspect ratio. This results in an overall heat input which is low compared to the GTAW process and which leads to minimal distortion. Low distortion, in turn, can eliminate postwelding operations of straightening or machining.

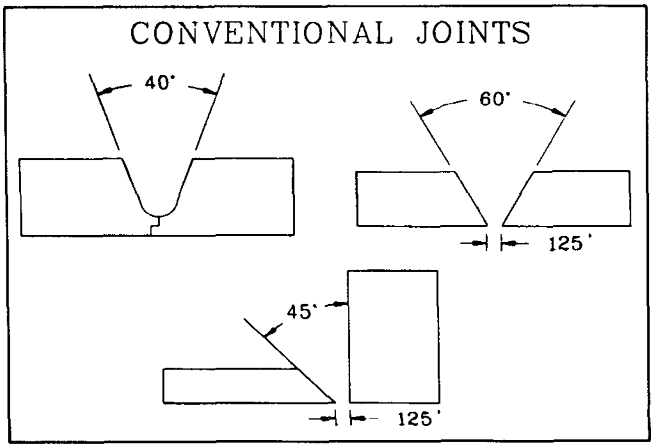
The disadvantages (Figure 6) mainly result from fit-up requirements which do not allow gaps, so parallelism and perpendicularity tolerances must be tightened on butt joints. Not only are machining costs increased, but drawing changes are usually required. In

LASER WELDING PROCESS

ADVANTAGES	-HIGH PRODUCTION RATE -LOW HEAT INPUT,MINIMAL DISTORTION -ELIMINATE STRAIGHTENING OPERATION -ELIMINATE MACHINING OPERATION
DISADVANTAGES	-CLOSE TOLERANCE MACHINED JOINTS -HIGH COST EQUIPMENT -DRAWING CHANGES REQUIRED

6. Advantages and Disadvantages of the Laser Welding Process

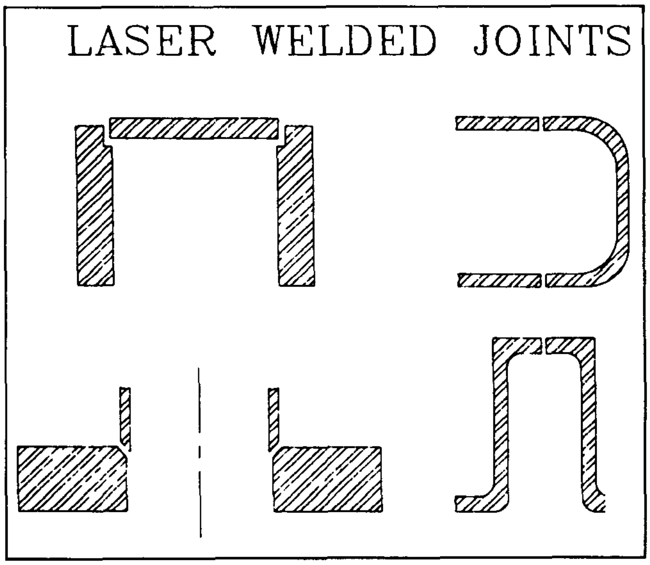
some cases, complete retesting of critical fabrications is mandated. The last disadvantage is the high cost of laser equipment and the higher maintenance/spare parts costs compared to GTAW.



7 Conventional Weld Joints for the Gas Tungsten Arc Weld Process

Weld Joints

Figure 7 illustrates three joints commonly used with the GTAW process The second and third joints (60° and 45°) are the most common for manual welding. These are usually not machined but flame-cut and handfinished The cost of these joints is usually comparable to the equivalent laser weld joint Machining on the spigot joint can exceed the equivalent laser weld joint, but these occur in special situations.



8 Laser Weld Joints

Figure 8 illustrates the joints which we have successfully laser-welded. Gaps greater than 0.005 inch are usually undesired. Out-of-roundness or final part alignment should be less than 0 030 inch (relates to depth of field of focus optic). The 45° tee joint permits positioning of the focus, plasma suppression nozzle, and cover gas apparatus.

Repair of Laser Welds

As with any welding process, defects in the weld may occur and do occur A strategy to manage these defects must be in place before shop welding occurs Figure 9 lists typical defects and the response to these defects. In general, the part is simply completely rewelded if joints are missed or not fully penetrated In situations in which metal must be added, the GTAW process is used to add the metal Sometimes the part is then laser-rewelded. Metal additions usually result from the keyhole relic or from joint expansion and/or poor joint fit-up.

REPAIR OF LASER WELDS

TYPE OF DEFECT	REPAIR METHOD
LACK OF FUSION	-REWELD WITH LASER
POROSITY	-EXCAVATE & GTAW REPAIR
UNDERCUT	-GTAW REPAIR
LACK OF PENETRATION	-REWELD WITH LASER
CRATER CRACKS	-EXCAVATE & GTAW REPAIR

9 Repair of Laser Welds

Cost Savings

The cost savings on heavier section laser welding occur at several points in the fabrication process. Much of the savings stem from the single-pass, autogenous weld. The overall heat input is low compared to the GTAW process which leads to minimal distortion. Reduced distortion is an attribute; however, in itself, it is not necessarily a cost savings. Cost savings from reduced distortion are generated from the elimination or a reduction in postwelding operations such as straightening or final machining. Machined products are generally rough-machined, welded, then finished-machined If final tolerances are not, say, less than +0.020, it may be possible to final machine components prior to welding in order to eliminate the final machining operation. The cost savings generated from the elimination of a postweld operation are often greater than the savings incurred as a result of reduced welding time.

Figure 10 illustrates typical estimated and computed costs from a 12-inch diameter cylinder which is a nominal 1/2-inch thick. A single butt weld is made. Repeating this process enough times so that work is efficient, an accounting is made of the major operations. These are listed and summarized in Figure 10.

COST SAVINGS FROM LASER WELDING

OPERATION	GTAW		LASER	
	HRS	$	HRS	$
MACHINE PREPS	2	48	3	78
FIT & TACK JOINT	1	24	5	12
SETUP	5	12	1	36
WELD	2 5	60	25	9
FINISH WELD	1	24	5	12
TOTAL COST		166		147

COSTING RATES
MACHINE SHOP $26/HR
WELDING SHOP $24/HR
LASER SHOP $36/HR

10. Cost Savings from Laser Welding

Drilling With Nd YAG Laser to Achieve Resultant Flow Characteristics

Mark D. Mello

Applications Engineer, Laser Fare Limited Inc.
One Industrial Drive, South
Smithfield, RI 02917

As experience has unfolded, Laser Fare has been presented with a variety of aerospace hardware components requiring anywhere from one to thousands of holes. Further experience has indicated that aircraft engine manufacturers, in constantly striving to decrease fuel consumption yet improve performance, have been faced with operating certain components at higher temperatures than ever before. In an effort to prevent the engine from turning into a glob of molten metal, it has become evident that a flow of cooling air is essential on some components and a more uniform mixture of combustion gases apparently is required in others.

In the former case, this consists of providing a pattern of many small, yet controlled, diameter holes in turbine nozzles, shrouds, and buckets.

In the latter case, it involves installing various sizes and quantities of holes in combustion liner components.

The typical configuration in this case requires a varying pattern of holes of diameters from .018 inches to .250 inches and at entrance angles to the surface of the part ranging from 10 degrees on up to normal (90 degrees) to the surface.

An item of prime consideration is flow characteristics which require, because of the shape of laser drilled holes, to percussion drill from either the inside of the liner wall, or from the outside, depending on the desired results. Hole configuration and its effect on flow characteristics will be discussed later.

Utilizing to the maximum the inherent flexibility and accuracy of the laser, five axis of motion and computer numerical controls, the tooling is very basic and constructed of an easily fabricated aluminum tooling plate. Programming is produced in a basic form also. Sub-routines for various hole patterns and spacing are called upon and inputed as required. Laser optics typically include a plano convex lens with a five inch focal length. The result is a beam with a low convergence angle and relatively long effective depth of focus. Oxygen co-axial gas assist is supplied through a nozzle which is positioned within .250 inches above the part being drilled.

Percussion drilling is becoming an established procedure when processing large quantities of holes of this type. The limitations are hole diameters under .030 inches with a depth to diameter ratio as high as 30 1. When considering part thicknesses under .100 inches, three to four pulses are required to break through the walls of these parts and the remaining bursts of energy are utilized in sizing and minimizing taper. Until break through, most all material is, of course, removed through vaporization. The bulk of the remaining material is shot out the exit side in the form of a stream of hot glowing globules and a "Fourth of July" shower of sparks.

Attempting to explain why a percussion drilled hole of this ratio is true, leads us to the realization that the phenomena of "light pipe effect" apparently is allowing us to drill holes with good diameter control throughout their length and truly in excess of the optics working depth of focus.

Cosmetic problems are of concern with aircraft hardware. However, a spray coating of anti-spatter does minimize the build-up of sprayed molten material or recondensed vapors. The remainder is removed through a light sanding with emery cloth. On a production basis, a vibratory tumbler or abrasive flow could readily become an integral part of a laser work station.

In these applications, there is no question that the laser is the most effective way to do this job--obviously there are other methods, but none so economical or timely. Consider, if you will, conventional drilling, electrical discharge machining, stem drilling or what have you. The laser's flexibility, combined with multi-axis capability, minimal tooling and monitoring will most assuredly become the key to a work center concept with its inherent cost and inventory advantages.

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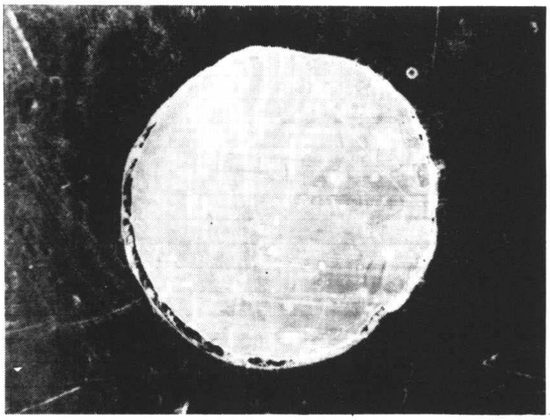
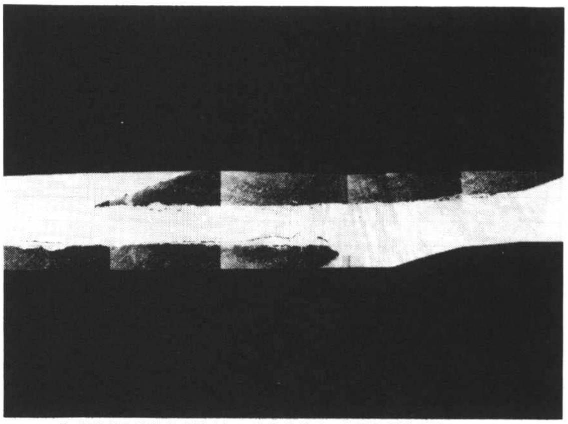
As previously mentioned, achieving desirable flow characteristics in aerospace hardware has led to some interesting findings. This has, and will undoubtedly continue, to have an effect on product design, drawing delineation, and methods of manufacture.

First, in defining flow characteristics of a particular component, a modeling program utilizing ideal characteristics is employed. It includes the assumption of a perfectly round, smooth hole as the basic geometry. The assumption does not necessarily apply to Nd:YAG laser percussion drilled holes. As seen in the pictures below, the hole can be slightly elliptical as well as containing localized globules over the length of the hole.



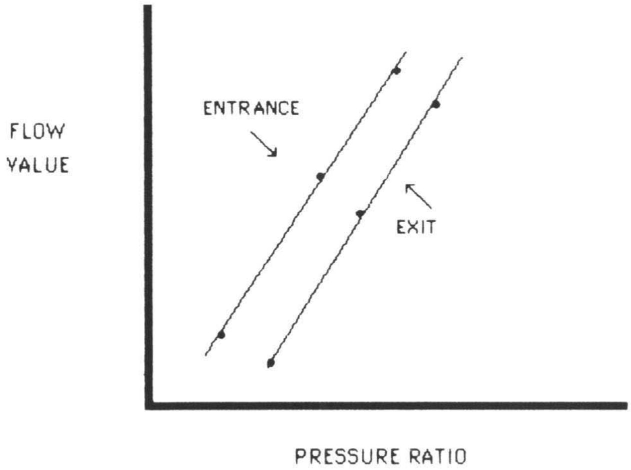
TRANSVERSE CROSS SECTION
OF LASER DRILLED HOLE



LONGITUDINAL CROSS SECTION
OF LASER DRILLED HOLE

There is usually a significant difference between the plug gauged diameter, which is the typical method of diameter inspection, and the true effective flow area of the hole. The difference can be as much as a 10 percent increase in the effective area. The phenomena has led to the increased usage of the term "drill to flow" on blueprints with geometric diameters being given as reference only. Flow areas have become the primary concern.

Another characteristic of Nd:YAG laser drilled cooling holes is the effect on flow values depending upon the direction of flow versus direction of drilling. As seen from the chart below, there is a decided increase in flow when the direction of air flow is the same as the direction from which the hole was drilled. This is due to the geometry of the hole from entrance to exit and its effect on flow losses as it enters, travels through, and exits the drilled hole. While this result may not be significant when considering one or two drilled holes, we can easily visualize the consequences of neglecting this effect when drilling a component requiring 10,000 to 20,000 holes.

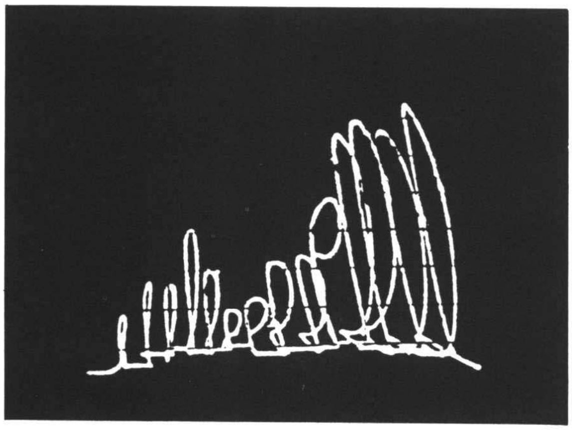


FLOW DATA FROM Nd:YAG LASER HOLE DRILLING

As it so often happens, every new technology seems to breed a new, different and perhaps revolutionary quality control technique.

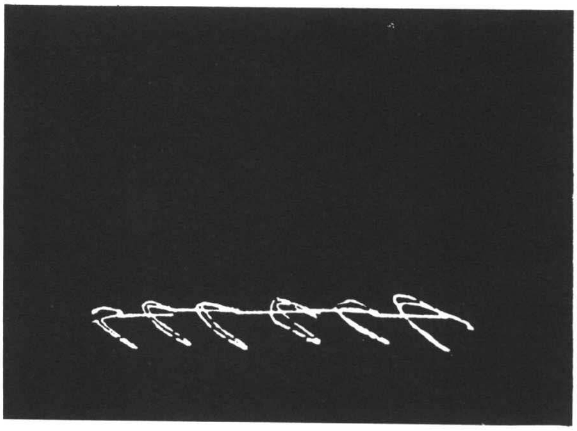
Anticipating the need to provide and monitor the quality of small laser drilled holes, we have recently entered into a feasibility study utilizing non-destructive testing techniques.

Eddy current, if it could prove effective in this case, seemed to be as "idiot proof" a system as one could expect. Results, although preliminary, are encouraging and as illustrated below, the pattern differentials are quite apparent.



small hole large hole

POSITIVE INDICATIONS
OF
EDDY CURRENT TESTS



small hole large hole

NEGATIVE INDICATIONS
OF
EDDY CURRENT TESTS

Realizing that the electro-magnetic characteristics monitored by the pick-up coil are in the component's conductivity, permeability, mass and homogeneity; it seems logical that evidence of microcracking and the resolidification layer could be detected. Results are inspiring, but continued testing, verification and calibration are required prior to any universal acceptance as a viable quality inspection technique.

If it proves as successful as we might expect, we can immediately visualize an eddy current technique as integral to the laser work center. Decreasing inspection time, increasing production--perhaps machine monitoring--will help to alleviate any concerns over hole integrity on critical aerospace components.

With the advent of this type of hardware, certainly the laser is shedding the cloak of "non-traditional". Its inherent effectiveness in these applications is in all probability "the only way". It will readily lend itself to multiple machine work centers with extreme capability of flexibility and implementation. Tooling is truly minimal, utilizing the multi-axis capability of computer numerical controls to its maximum.

Competitive technologies can perhaps do a job, but with the advent of "just in time" inventory considerations, a manufacturer cannot wait for weeks (or months) for hard tooling nor could they, in most cases, justify the expense.

Flexibility, efficiency, tooling, production cycles, and as we have seen, the exploitation of flow characteristics, all add up to the fact that percussion drilling with laser most assuredly creates a new chapter in the never ending saga of Manufacturing Aerospace Hardware.

Acknowledgements

The author wishes to express thanks to Randy Myers of Laser Fare Limited Inc. and to E. C. Jones for their cooperation and technical assistance in compiling information for this paper.

Applying lasers for productivity and quality

David W. Porter

Development Operations-Metal Joining, Pratt & Whitney, United Technologies Corporation
Mail Stop 165-44, 400 Main Street, East Hartford, Connecticut USA

Abstract

The laser, with its intense beam of focused pure light, precisely controlled and moved by computer, is being increasingly used for processing aircraft gas turbine engine components. Pratt & Whitney uses both solid state and gas lasers for a variety of applications including welding, cutting, hole drilling, hardfacing, and marking of parts for identification. Laser processing provides increased productivity and reduced cost compared to conventional methods.

Specific uses of lasers in gas turbine fabrication are described and compared against the prior method of manufacture. Tooling approaches and metallurgical effects associated with various laser processes are also discussed.

Introduction

The gas turbine engine is a complex piece of rotating machinery made up of a variety of very difficult to machine materials. The engine, to perform in its operating environment, relies on the latest state-of-the-art in materials, and similarly on the manufacturing processes needed to craft the components. There appears to be a natural partnership between the two, with high technology being the common denominator. The laser has complimented the evolution of P&W engines by providing a new manufacturing capability when it was needed and providing a more cost effective manufacturing method. In some cases it became the only way to do the job.

Any discussion of how the use of laser for producing engine hardware resulted in increased productivity and quality must start with a recognition of the benefits lasers offer.

Benefits

The laser output, directed and focused by optics, results in a highly concentrated spot of energy. For low power solid state lasers under 1000 watts, the spot size is approximately 0.005 inch and for high power CO_2 lasers over 1000 watts, the spot size is 0.020 inch. This translates into minimal heat affected zones (HAZ) and minimal distortion during welding, a plus in crack-sensitive superalloys. The small spot size also results in narrow welds similar in size and geometry to electron beam welds (Figure 1). The laser, when compared to electron beam processing, frees the welding engineer from the constraints of a vacuum chamber, magnetic influence on the beam, and the limitations of electrical circuitry and part size.

As the laser evolved, so did improvements in machine tool and system controls. Today there are reliable CNC laser systems that provide precise and repeatable production equipment with programmable features to control both the laser parameters and machine tool positioning functions. These features allow versatility, flexibility and the ability to change over easily for processing engineering changes dictated by the engine development cycle. This also results in a minimal need for large amounts of hard tooling. The sophisticated laser systems available today lend themselves to the next level of automation where the laser functions as part of a total Flexible Manufacturing System cell or similar automation line, or as a central power source delivered to a work station on demand.

This report focuses on laser applications for welding, hardfacing, drilling, and cutting at Pratt & Whitney. Specific parts are discussed along with the benefits of increased productivity and quality associated with the change to laser processing.

Welding

Electron beam welding introduced into manufacturing shop areas during the 1960's gave P&W an opportunity to experience the benefits of narrow deep penetration welds with minimal heat affected zones and minimal distortion. The early 1970's saw lasers come on to the scene offering the same potential benefits, but without some of the restrictions normally associated with E/B.

For the initial work a number of candidate parts such as impingement tubes, baffles, and covers were selected because of their size, production volume and their complicated welds which required skilled manual welding techniques. The first parts to be converted to laser welding were the JT9D-7 and -70 impingement tubes, assemblies critical to the distribution of cooling air in turbine blades. The impingement tube assembly is made up the tube, end cap, and root wedge.

Conventional manufacturing techniques consisted of a combination of electron beam and manual plasma-arc welding (PAW) of the root wedge detail, and manual Plasma-arc welding of the end cap. The manual operations for the tip cap required a skilled welder who, working through rubber gloves and gauntlets inside an atmosphere chamber, picked each piece up, electrically grounded it and made the weld (Figure 2). This process resulted in the occurrence of excess weld build up which led to increased inspection costs and post weld dressing to insure part uniformity. A continuous wave 600 watt Nd:YAG laser is now routinely welding impingement tubes and has virtually eliminated the costly post weld operations. Parts of uniformly high quality are produced in a fraction of the time and at far lower cost than the manual welding and E/B process it replaced.

The impingement tube details are fixtured and automatically laser tack welded on each side with a brief burst of light energy. The tack welded assembly is then loaded into another fixture for automated laser welding of the circumferential root wedge joint (Figure 3).

Under computer control, the fixtured part is rotated and moved at the programmed rates required by the joint geometry and other variables. The resulting weld is characteristically smooth and uniform, leaving no trace of the tack welds and eliminating the need for post weld dressing.

For tip cap welding, six assemblies are installed in a welding fixture designed to hold the parts in precise alignment (Figure 4). Using programmed control the fixtured parts are moved into position and each part laser welded around the tube contour.

Using automated continuous wave YAG laser welding, requiring no special operator skills, an overall saving of 93 percent in processing time has resulted. (Figure 5).

Baffles similar to impingement tubes perform the same function of distributing cooling air to turbine vanes. The baffle is used in turbine vanes to prolong part life and because it is made in high volumes it also became a candidate for laser welding. An axial seam weld and a cover closure weld were changed over to laser welding for a three to one increase in productivity and 30 percent reduction in cost (Figure 6).

A multi-position rotary indexing system allows the unloading and loading of parts continuously and simultaneously with the weld operation (Figure 7). The part, protected by an argon shield gas, is indexed under the laser beam. Welding is initiated at programmed rates along the part contour. This process is highly repeatable and results in uniform high quality welds with no secondary weld blending.

A 400 watt continuous wave YAG laser has also been successfully employed to replace a brazing operation to attach metering plates to the end of turbine blades (Figure 8). Metering plates, as the name implies, regulate air flow through the hot turbine blade. Brazing was selected because of the problem of joining a very thin detail to a large, heat-sensitive mass. The process resulted in a substantial number of rebrazes to get the required braze coverage. Switching to laser welding reduced the average processing time from 18 minutes by brazing to one minute by laser. The laser welding added the benefit of eliminating post braze operations.

Hardfacing

Another area of high cost savings has been in the application of laser for hardfacing the shroud notch areas on turbine blades to reduce wear on abutting surfaces (Figure 9). The established process was manual TIG hardfacing which required excessive handling of parts for fixturing, and shielding airfoil surfaces to protect them from spatter during the manual fusion melting of the cobalt alloy hardface material. To achieve sufficient hardface buildup, the operator repeatedly fed in filler wire while manipulating the welding torch. This repeated melting and solidifying required multiple passes over a relatively long period of time. This resulted in excessive heating of the crack sensitive blade material, leading to cracking of the hardface and base metal materials in and adjacent to the interface. The process resulted in high rework of parts.

A United Technologies Research Laboratory CNC 6KW CO_2 axial cross flow laser system has been brought on line to replace the costly manual hardfacing of turbine blade shroud notches.

Special fixtures with copper chill inserts position the cast cobalt base hardface material on the blade shroud notch. Programmed control of laser oscillation, beam focus, and power combine to melt the insert and to distribute it over the notch surface. The part then rotates automatically, aligning the opposite shroud notch to repeat the operation. This change lessens the need for operator skill and closely controls dilution of the hardface into the base metal, resulting in consistent hardness in the finished blade. Manual hardfacing averaged 3.2 minutes per blade with up to a 30 percent rework rate. High power CO_2 laser hardfacing takes 1.3 minutes per blade and reduced rework to 1-3 percent.

Drilling

There is an ever increasing demand to improve operating efficiencies of gas turbine engines. The designer knows it is possible to meet this goal if the absolute temperatures can be increased. The goal is being met through significant advances in materials development and by finding new, improved ways to cool engine components. The latter is accomplished as a partnership between design and manufacturing capabilities.

Initial turbine blade and vane cooling schemes relied on air being circulated through internal passages cast into the turbine airfoils. This has been followed by the addition of large number of accurately sized and positioned small holes to direct cooling air in metered amounts to precise locations on the airfoils.

Initially Electro Chemical Machining (ECM) and Electro Discharge Machining (EDM) were used to install the cooling holes because the superalloys used were difficult to machine by conventional methods (Figure 10).

As the number of holes and diversity of position increased, it became evident that a process more flexible and less costly than ECM or EDM was needed. Laser, with its versatility and potential for automation, was the obvious choice.

The first two laser systems adapted to hole drilling of turbine airfoils were Neodymium glass lasers (Nd:Glass) mounted on a modified five-axis CNC Bridgeport milling machine.

These systems were capable of producing airfoil holes at the same rate as the EDM process, but were more than five times faster installing deep holes, over .500 inch long, in the platform areas of turbine vanes.

These systems, installed in 1978, were supplemented by ruby laser systems built by United Technologies Research Center in 1979. These new lasers, driven by improved software, proved their versatility in reacting to major hole location design changes. An engineering change which would normally require six to nine months for the EDM process to incorporate could now be accomplished in a matter of hours.

A large number of these lasers handle the production requirements for commercial engines such as the JT9D, and the newest engine models such as the PW2037 and PW4000.

The Nd:Glass lasers were slow(one pulse every four seconds) and hole quality, hole taper, and hole recast surface were less then desired. The ruby lasers improved the situation, pulse rates went to one pulse per second, recast was less and hole quality improved.

Last year these systems processed more than 50,000 turbine airfoils installing more than 8 million .013-.030 inch holes varying from .080 to .850 in. long, at tolerances of a few thousandths. Each laser has five axes of motion: X, Y, Z, and two rotary (Figure 11).

The laser evolution as it applies to hole drilling has not stopped. Newer Nd:YAG drilling systems are now coming on line with hole qualities equal to ruby systems, but at considerably higher pulse rates(4 pulses per second) which translates into higher throughput.

Cutting

The application of laser cutting using Nd:YAG and CO_2 laser systems has followed the initial welding hardfacing and hole drilling applications. Cutting with laser offers generally the same benefits that are universal to lasers, such as flexibility, ability to automate, and ease of beam manipulation. However, there appears to be more trade offs to

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