Printed in U.S.A.

71-GT-21

an ASME publication

$2.00 PER COPY
$1.00 TO ASME MEMBERS

Design Considerations in Inertia Welding of Turbocharger and Gas Turbine Components

C. D. WEISS
Applications Engineer

L. J. MOEN
Research Engineer

W. M. HALLETT
Sales Supervisor

Inertia Welder Department
Caterpillar Tractor Co.,
Peoria, Ill.

This paper begins with a statement of the acceptance and use of inertia welding in the gas turbine field. A short explanation of the inertia welding process follows. Categories of welds discussed are solid inertia butt welds; tubular inertia butt welds; and angular-annular inertia butt welds. An example of the first category is a bimetallic engine valve. The second category is typified by steel shafts joined to superalloy rotors for turbines. The joining of wrought superalloy disks to cast superalloy blade rings to produce a composite wheel comes into the third category. The effect of welding parameters on strength and microstructure, as well as design and process changes required for inertia welding are related. In conclusion, basic considerations for utilization of inertia welding are expressed.

Contributed by the Gas Turbine Division of The American Society of Mechanical Engineers for presentation at the Gas Turbine Conference & Products Show, Houston, Texas, March 28-April 1, 1971. Manuscript received at ASME Headquarters, November 27, 1970.

Copies will be available until January 1, 1972.

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS, UNITED ENGINEERING CENTER, 345 EAST 47th STREET, NEW YORK, N.Y. 10017

Design Considerations in Inertia Welding of Turbocharger and Gas Turbine Components

C. D. WEISS L. J. MOEN W. M. HALLETT

The Inertia Welding Process is gaining broad acceptance for its ability to produce a reliable and consistent solid-state bond under high rate production conditions. It is a unique friction welding process that makes highly efficient use of stored kinetic energy for all of the heating and for much of the forging of the bond. Although it is most frequently applied to ferrous materials, parameters are readily controlled to produce excellent bonds in most metal systems.

This paper discusses a category of welds which is of interest to engineers engaged in the gas turbine field — the welding of low alloy steels and wrought superalloys to cast superalloys. Inertia Welding is particularly useful in this area because of the ability of the flywheel to deliver the high energy input rates needed to forge-weld these heat-resistant materials.

INERTIA WELDER PROCESS

The Inertia Welder produces welds by converting stored kinetic energy to heat at the weld interface via friction. The process is simple. One member is gripped firmly in a stationary clamping device. The other member is coupled rigidly to a properly sized flywheel. The flywheel is then accelerated to a predetermined angular velocity. The stored kinetic energy is then rapidly converted to frictional heat at the weld interface when the two members are brought together under a relatively high thrust force. Rotation stops when the flywheel energy is completely discharged. Weld characteristics are determined and controlled by three parameters — initial velocity, flywheel moment of inertia, and thrust load. Machines need only control thrust pressure and spindle speed to control the process once the flywheel size has been selected. Different materials prefer different values for these parameters.

SOLID INERTIA BUTT WELDS

One type of joint between high-temperature materials and steel is the inertia welding of bimetallic engine valves where a high hot strength

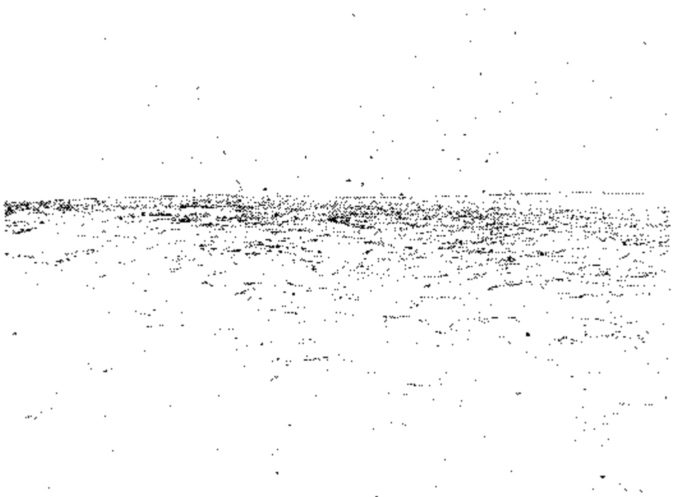

Fig. 1 Microstructure of inertia-welded Silcrome 10 (top) - 8645 (bottom) valve. Neg: M39857; Etch: 1 percent nital, chromic. 100X

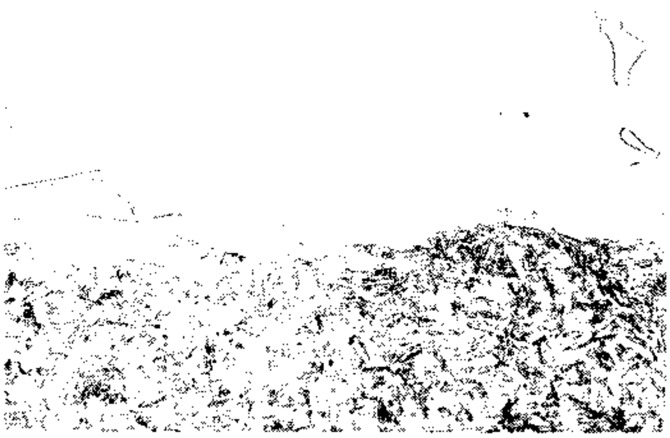

Fig. 2 Microstructure of 713C (top) - 8630 (bottom) turbocharger joint inertia welded at 1780 fpm. (Note: Crack along carbide). Neg: M22732; Etch: 1 percent nital. 500X

and hot corrosion-resistant valve head material, such as Silchrome 10N, is welded to a wear-resistant steel material, such as SAE8645. Joint design is not as critical in these small welds, so both members may be machined to the same diameter. No difficulties were encountered in making the valve welds as indicated by the sound clean microstructure of the Silchrome 10N-SAE8645 joint in Fig. 1. Tempering treatments were applied to the valve welds to soften the weld flash. The welding flash was removed after tempering when it was in a machineable condition. Rotating beam fatigue tests (endurance limit 60,000 to 65,000 psi) indicated that the weld has at least base metal properties. Fatigue fractures always propagated in the Silchrome 10N as might be expected.

TUBULAR INERTIA BUTT WELDS

One area of interest to turbine engineers is the welding of superalloy turbine rotors to steel shafts. During preliminary tests for butt welding Caterpillar turbocharger IN713C-SAE8630 wheel-shaft assemblies, serious cracks were found in specimen weld zones. Closer examination showed that the cracks followed thin transverse stringers of carbides in the weld zone. As weld conditions were varied in an effort to eliminate cracking and carbide formation, it became apparent that both were speed dependent. Figs. 2, 3, and 4 show that at 1780 surface fpm, cracks and carbide stringers were present; at 801 fpm cracking was eliminated, but carbide stringers remained; at 400 fpm carbides were substantially reduced; and finally at 267 fpm, carbides were

Table 1 Effect of Initial Sliding Velocity on Tensile Strength of SAE8630 - 713C Welds

INITIAL VELOCITY (SFPM)	ULTIMATE STRENGTH (PSI)
670	97,500
580	102,500
525	104,000
475	118,000
350	124,000
315	130,000

completely eliminated. As speed was reduced, the flywheel mass was increased correspondingly to maintain an adequate kinetic energy input. Reduced speeds and larger flywheels decreased the maximum welding temperatures and increased the plastic working in the weld zone, respectively. Three possible explanations for carbide elimination are: (a) the lower welding temperature may prevent solutioning and reprecipitation of carbides as transverse stringers; (b) the more severe deformation may shatter any elongated carbides; and (c) the carbides may be expelled with the flash. This speed effect has been observed on other turbocharger weld joints, such as IN713C to SAE4140. Tensile tests of the IN713C-SAE8630 welds illustrate the effect of the weld zone carbide stringers (Table 1). As the welding speed was progressively decreased and carbides decreased, the tensile strengths increased and

Fig. 3 Microstructure of 713C (top) - 8630 (bottom) joint inertia welded at 801 fpm. Neg: M22733; Etch: 1 percent nital. 500X

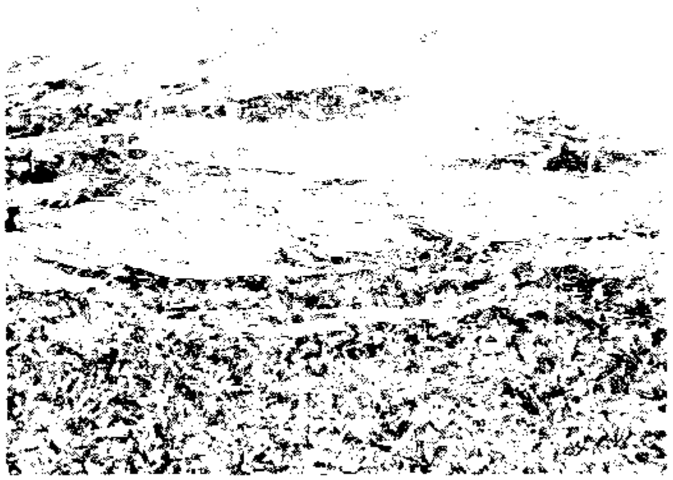

Fig. 4 Microstructure of 713C (top) - 8630 (bottom) - 8630 joint inertia welded at 267 fpm. Neg: M22734; Etch: 1 percent nital. 500X

Table 2 Tensile and Stress - Rupture Properties of Inertia Welds in IN713LC - IN718 Gas Turbine Rotors

SPECIMEN	TEST TEMP. OF	ULT. STR. PSI	YLD.STR PSI	ELONG. % (1 IN.)	REQ. AREA %
Initial Welds	Room	127,600	99,800	3.7	10.9
Initial Welds	Room	91,200	91,400	2.4	18.6
Initial Welds (Reaged)	Room	133,100	133,000	1.9	2.4
Initial Welds (Reaged)	Room	128,800	128,800	2.6	1.2
*IN713C	Room	110,000 Min.	100,000 Min.	3.0 Min.	- -
Final Welds	1200	152,400	125,600	4.0	5.3
Final Welds	1200	161,100	125,500	6.0	8.6

*SPECIFICATION AMS5391

SPECIMEN	TEST TEMP. OF	ULT. STR. PSI	YLD.STR. PSI	ELONG. % (1 IN.)	REQ. AREA %
Initial Welds	1300	75,000	0.1	1.6	7.7
Initial Welds (Reaged)	1300	75,000	0.1	0.1	2.2
Final Welds	1200	100,000	53.5	1.0	- -
Final Welds	1300	75,000	37.2	0.5	- -
Final Welds	1300	75,000	45.1	0.5	- -
Final Welds	1300	75,000	33.4	0.5	- -
Final Welds	1300	75,000	56.6	0.5	- -
**IN718	1300	75,000	23.0 Min.	5.0 Min.	- -

** SPECIFICATION AMS5663

HEAT TREATMENT FOR IN718: 1750° F.-1 hr. air cool, 1325° F-8 hr, furnace cool to 1150° F., 1150° F.-10 hrs.

the fracture location moved out of the weld zone.

Since the high hot-strength superalloy joint member IN713C was much more resistant to weld-forging than the low hot-strength SAE8630 steel member, the steel member was machined to a 1/16-in. larger diameter to help balance the forging. Double hexagon grips were machined into the massive portions of the members to minimize distortion from the high torques developed in the welding process. Steel-superalloy joints, such as the IN713C-SAE8630 joints, are normally welded in the fully heat-treated condition to refine the weld area grain size and to avoid soft carbon depleted zones in the steel, resulting from carbon diffusion across the interface during post-weld heat treatments. Fig. 5 shows the effect of applying IN901 post-weld heat treatments (2000 F -2 hr air cool, 1400 F -1 hr, oil quench) to an IN901-AMS6304 superalloy-steel weld. Note the dark etching layer which is soft coarse grained martensite and ferrite as compared to the much harder martensitic base material. Hardenable steel mem-

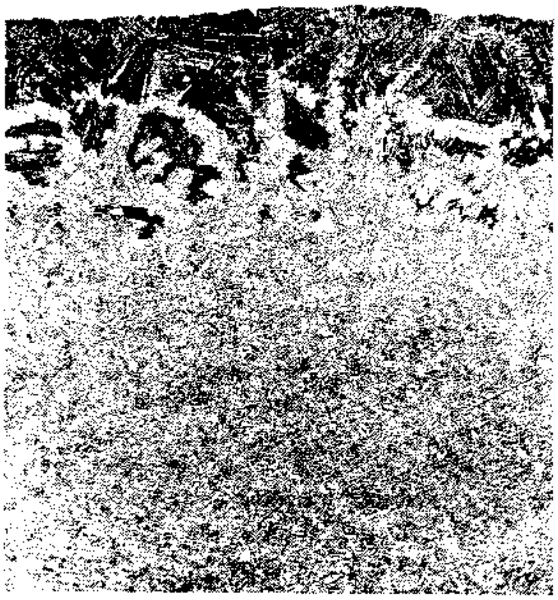

Fig. 5 Microstructure of 1N901 (top) AMS6304 (bottom) inertia weld after post-weld heat treatments. Neg: M40607; Etch: 1 percent nital. 100X

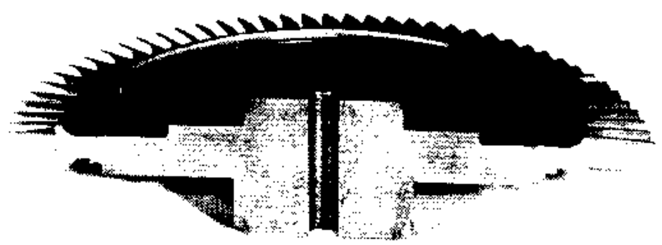

Fig. 6 Cross section of 1N713LC-1N718 inertia-welded rotor. Neg: 16254; Etch: 1 percent nital. 1/2X

Fig. 7 Microstructure of an initial 1N713LC (top) - 1N718 (bottom) inertia-welded rotor. (Note: MC carbides at bond interface). Neg: M35297; Etch: Marbles. 1/2X

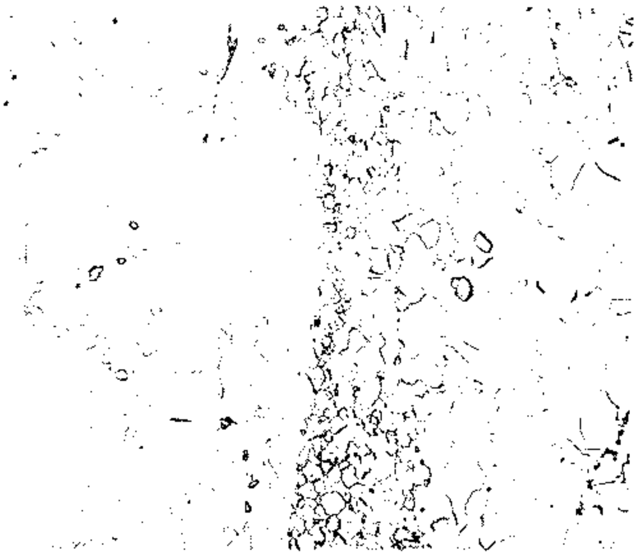

Fig. 8 Microstructure of a final 1N713LC (left) - 1N718 (right) inertia-welded rotor. Neg: M40640; Etch: Rollings. 500X

bers, such as the SAE8630, must be tempered after welding because the welds cool rapidly enough to harden the steel heat-affected zones. Steel-superalloy welds with preweld heat treatments usually develop base metal tensile strengths and slightly reduced ductility.

Steel members in the superalloy-steel joints should be selected with minimum necessary carbon contents. Higher carbon steels are generally weldable to superalloys with full joint strength. However, welding parameters for such combinations are usually more critical. Quench cracking of steels has not been much of a problem, but it is prudent to avoid high carbon contents in the more highly restrained joints such as angle joints. Welds made with steel members containing free-machining elements, such as sulfur, phosphorus, selenium, or lead, should be avoided unless lower tensile strengths are acceptable, because free-machining phases are realigned transversely during welding to produce weak paths for fracture propagation. Also, the low fusion temperatures of the free-machining compounds may cause hot-short cracking in the more highly restrained joints.

Table 3 Material Combinations Welded for Turbine Applications

SUPERALLOY TO SUPERALLOY

IN713C-IN718	IN713LC-IN718	GMR235-A286
U700-U700	IN100-IN718	WASPALOY-IN718
WASPALOY-IN901	WASPALOY-WASPALOY	IN901-IN901
STELLITE 220-STELLITE 220	HASTX-HASTX	RENE 41-RENE 41
TD NICKEL-TD NICKEL	ASTROLOY-ASTROLOY	HS 21-HS 21
	IN600-IN600	

SUPERALLOY TO STEEL

IN713C,LC-1036	IN713C,LC-4140	IN713C,LC-5140
IN713C,LC-NITRALLOY J	IN713C-8630	IN713C,LC-EN24
IN713C-AMS6304	IN713LC-D979	HS 31-1036
GMR235-1040	HS 31-8630	GMR235-4130
GMR235-8620	GMR235-8630	STELLITE 21-8630
B1900-4340	U710-4140	M246-5140
WASPALOY-VASCOMAX 250	WASPALOY-AMS6304	WASPALOY-8645
IN718-AMS6304	IN901-AMS6304	HASTX-1045
RENE 41-4340	IN751-1045	IN751-1020
IN600-1018	IN600-304	

STEEL TO STEEL

410-1045	416-416	416-1040
17-4PH-17-4PH	17-4PH310	17-4PH-347
CARP 20-1020	CARP 20-1045	

TITANIUM TO TITANIUM

TI(6-4)-TI(6-4)	TI(6-4)-TI

ANGULAR-ANNULAR INERTIA BUTT WELDS

Another area of interest to turbine engineers is the welding of wrought superalloys to cast superalloys, usually in the more highly restrained angle or annular joints. Composite wheels with cast blade rings welded to wrought disks are desirable to produce the best properties in both locations — high strength and low cycle fatigue resistance in the disks and high creep resistance in the blades. A typical series of development welds were made between IN713LC ring castings and IN718 disk forgings. The first two welds were made with both members in the fully heat-treated condition because of the possibility of cracking, resulting from the combination of disk aging contraction stresses and weld residual stresses. Complete heat treatments after aging were avoided because of the possible detrimental effect of the IN718 solution treatment of the IN713LC and the large weld zone grain sizes which would result.

Fig. 6 illustrates the geometry of the 30-deg angle joint and the large heat and deformation affected zone in the IN718. The sluggishly aging IN718 weld zone was completely solution treated and did not reage during cooling from the welding temperatures while the higher hardness content IN713LC was solutioned but reaged to the base metal hardness level. Fig. 7 shows an unbonded interface section adjacent to a long MC carbide stringer.

The second rotor was spin tested to 40,000 rpm with failure, although cracks were observed to grow from the unbonded sections of interface. Tensile and stress-rupture specimens were taken across sound carbide-free portions of the weld in the unspun rotor, and test results are shown in Table 2. Tensile and stress-rupture properties were poor. Some specimens were partially reaged (1325 F for 8 hr) to reharden the IN718 weld zone to base metal levels without drastically overaging the base metal. The reaging improved the tensile properties but worsened the already poor stress rupture properties. Also, the reaging did indeed restore base metal hardness without altering the hardness and microstructure of the base metals.

Subsequent IN718-IN713LC rotors were welded with the IN718 in the solution treated conditions, since heat-treatment cracking was found not to be a problem. Welds were made with higher loads, energies and velocities to eliminate carbide layers, unbonded interface segments and weak welds through more extensive flashing and deformation in the IN713LC, Table 2. Final machining was done on these rotors before aging to eliminate stress raisers, such as notches which might cause heat-treatment cracking. The complete aging cycle of the IN718 was then given to the welded rotors. Final microstructures displayed fine grain weld zones with uniform hardness as shown in Fig. 8. Tensile and stress-rupture properties of the improved joints displayed base metal tensile strength and stress-rupture strength with slightly reduced ductility (Table 2).

SUMMARY

Inertia Welding is applicable to many combinations of iron, nickel, and cobalt base superalloys and steels for gas turbine and turbocharger construction. Table 3 lists some of the weldable combinations. Required parameters for Inertia Welds may be calculated by simple mathematical formulas. Superalloy-steel welds are best made with both members in the fully heat-treated condition. Superalloy-superalloy joints with a heat-treated wrought member should be welded in the solution-treated condition and aged afterward. The joint member with the lowest hot strength should have a larger OD than the other member to ensure sufficient deformation on both sides of the joint line. Strong grips should be machined on both members of angle joints to transmit the high torque and thrust loads needed for welding. Sufficient OD stock should be provided to insure cleanup of weld surface imperfections — before final heat treatment in the case of the superalloy to superalloy welds and after tempering in the case of superalloy to steel welds. Carbon contents of steel members should be minimized where possible to reduce chances of weld hot cracking or quench cracking. Steels containing free-machining elements should be avoided unless reduced properties are tolerable.