A Manufacturing Process: Wire Electrical Discharge Machining (WEDM) Of High Stressed Turbo Machinery

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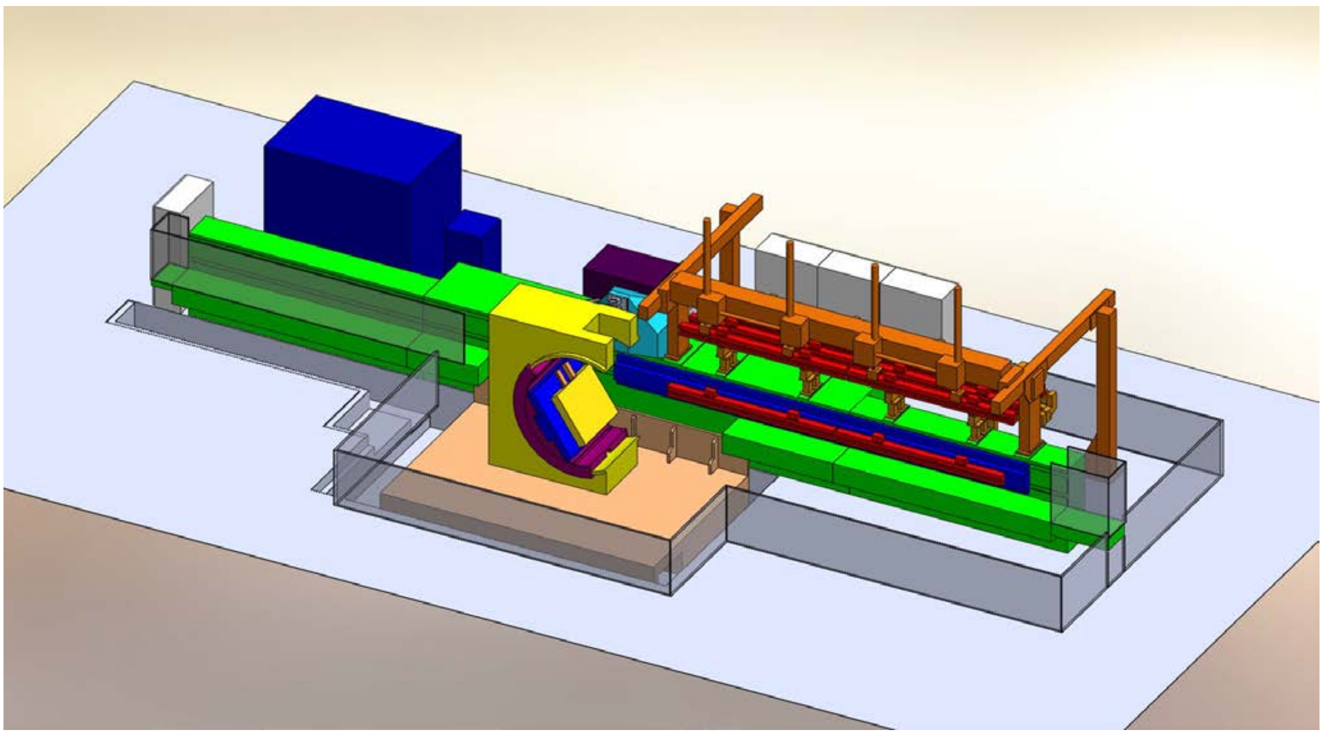
Background:

The gas turbine engine has many components, but the spinning turbine disk(s) is the most highly loaded mechanically, plus the high operational temperatures compounding that loading. A turbine disk is designed with uniquely-shaped slots around the it's periphery which is used for blade attachment. These attachments are also found highly stressed because of centrifugal speeds and the heated region of the disk. Attachments are also known as blade-slots, and are typically double-lobe or single lobe in design. For proper operation of the blade its alignment and overall disk loading, all the slots must be precisely placed equally around the periphery of the disk by areas called contact-planes.

It is these contact planes inside the attachment slot, which hold the tightest dimensional and profile tolerances to themselves, plus back to the disk itself. The most common manufacturing process for production of either single or double lobe slots is broaching. For decades large mammoth broaching machine-tools have push or pull long bars containing cutter segments through the various widths of disks. These disks are made from high temperature resistant materials to survive in this hostile environment which is also very resistant to shearing. To overcome the intrinsic resistance of the material to shear, the manufacturing process must use pure brute force, driving progressively sized cutter-teeth through the disk, controlling the removal of smallest chips of disk material, hence the long length of broach-cutter-bar. Today, various types of broaching methods are used by the machine-tool manufacturers and the retrofitters in attempts to use design innovations to overcome the high shear resistance in this machining process.

The most successful has been the Direct-drive gearbox design with hydraulic action being the secondary selection. Using 100 to 200 horsepower electric motors directly driving large gear-reduction units to move the 12 to 16 segments contained inside the broach-cutter-bars. Sometimes these bars would contain only the pre-broach cutter segments for going through the disk material, because of its thickness and slash-angle. This then requires another complete new set of cutter-segments, in their own second bar, to be used for just finishing the final sizing of each slot.

Often during the bar's travel, where it is progressively broaching the slot's profile, the cut-chips get hot enough to momentary-weld themselves to the broach-cutter tooth forms. This requires a operator to aggressively swipe a stiff wire brush, in an attempt to manually dislodge the tightly adhering chip. This human involvement, if not performed continuous, will result later in surface finish problems. One must equally aware of the use of specialized cutting oils that are filtered and temperature controlled for optimum process control. Unfortunately, these cutting oils require the broach-operator to have extra personal protection equipment [PPE] and oil-mist extraction for clean breathing? These cutting oils require constant monitoring for contaminations and concentration, as well as their disposal when found depleted.

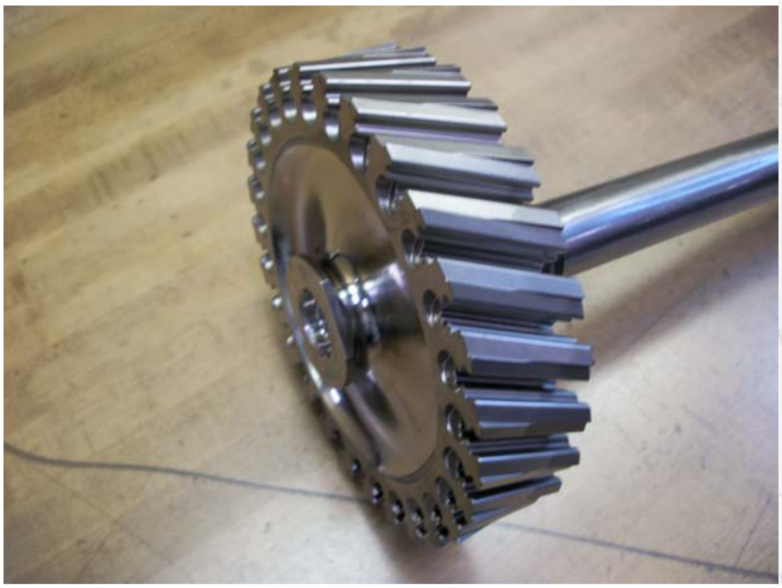


What is often missed when cycle times are calculated is the extensive pre-setting of the 8 to 14 broach-cutter-segments. All of these segments must be positioned and aligned in their Broach-Bar, then torqued down. Many hours are spent in this phase of set-up, just shimming and adjusting each of the segments, only to find a dulling cutter later needs exchanging, repeating the adjusting procedure.

The next large attribute to broaching is its work-holding fixture, also often referred to as tooling. After Engineering has finalized their disk design; for material, size, slot number, P-point position, and slash-angle the tool/fixture design can be started. Here is the next set of decisionary points; manual or automated indexing, sacrificial inserts or plain cutting, hydraulic or mechanical gripping. This phase in the fixture's design is where it has been found that the design features of spacing-error can be directly affected. All of these features drive the design cost, its fabrication cost, and it's lead-timing. Which, in-turn sets the schedule and total cost for the fixture itself. The disk's slash-angle determines a force vector on the disk to move, caused by every advancement of the broach-cutter-bar, only to be countered by the tightened grip of the fixture's design. Subsequent slotting builds even more stress in the next slot being cut. This requires measurements of the first-to-last slots for their variances, and shows why the need for hydraulic gripping, because of its superior clamping.

On top of this, new regulatory regulations are mandating the monitoring for abusive machining, with broaching being a prime focus. Which is the monitoring of defects as they are being produced? Sensors can be designed and inserted into this tooling/fixture for this use. These sensors provide electronic feedback and a signature of a particular set of assembled broach cutters. With monitoring and cutter-tooth experts a sets of ranges can be programmed for alarms inside the machine-tool, of pending problems or cutter wear notification, before major damage can occur.

The purpose of this paper is to present is an alternate to broaching. Yes, there is a known milling cutter process being used in place of broaching, but research has found the early need to design the disk first for a rotating shaped cutter, or a high rate cutter production process. Offering the use of using milling-shaped-cutters requires the actual slot to be first designed to reflect that approach. Present slot designs with the material systems used on gas turbine disks cannot tolerate the large perishable tooling costs.



Research Focus:

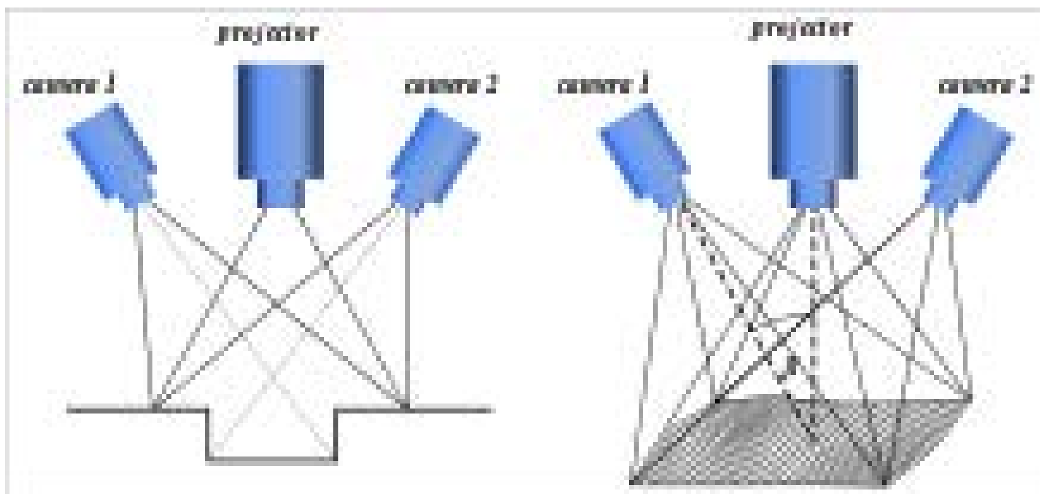
This abstract will focuses on an innovated alternative method of producing attachment slots by use of multi-pass (MP) W-EDM in turbo machinery materials, with comparisons of broach versus MP-WEDM slotting in rotational disks. MP-WEDM provides increased dimensional stability, responsiveness to design changes, lower perishable tooling inventory, greater human user experiences, and the introduction of flexibility, with increased control to this manufacturing process.

The initial machine-tool of the average precision quality, in a ready to-use condition starts at one million dollars (USD). Today, that basic machine-tool will often be found as a retrofit, once originally built years ago, then surplus, and stored till a buyer with a tailored retro-program can be matched. This retro-program is a great opportunity for many of today's innovations to be incorporated into the rebuild as options. In addition there are the complicated transportation expenses for the oversized loads, with special permits and handling equipment, with its official equipment operator. Equally important is the machine-tool's extensive floor foundation, to help maintain the accuracies and precision necessary for a production environment.

The major expense in daily broaching is the actual broach-cutter-segments themselves. There are many critical dimensions to control, not only for slot conformity, but the actual manufacturing process itself. From cutter tooth geometry, the progressive stages of each cutter, to the CAM model used for simulations of the cutting actions, and later for cutter sharpening. Stack tolerances and budgets are iterated and optimized by various experts, till a series of compromises are reached. Even selection of the segment's material needs to be a balance of availability and performance. Other broach-cutter segment factors include; heat treatment, coatings, cryogenics processing, clearances, back-taper, and the number of segments. Finally the number of extra segments needs to be determined for exchanging, while sharpening takes place. Costs of broaching can easily spiral out of control if these items are not design optimally.

Successful placement for both position and spacing of all the slots in the disk is highly dependent upon the work-holding fixture. Again there are decisions necessary for style or type of fixturing, from manual clamping to hydraulic with solid or expanding location diameters, to the indexing method. The indexing method has the vector forces from the slash-angle always twisting on its locking features. Hence the extensive design and use of premium materials, for self-centering from possible wear.

Advancements in CMM inspection have allowed the sophisticated hard gaging to become obsolete. This hard gaging and their set-masters were in constant debate and calibration on their use or design. An Optical Comparator can be a quick tool for checking the profile-of-a-line for its basic silhouette, but is often misused in the evaluations for profile-of-a-surface. Broach cutters can be viewed for wear using the optical comparator, but for profile acceptance the CMM or S-L inspections must be the only source.



Nomenclature:

WEDM = Wire Electrical Discharge Machining

MP-WEDM = Multi Pass Wire Electrical Discharge Machining

P-Point = a gathered position, identified by design, just above the periphery of the disk, where

Centerlines of the slot and the width of slot converge to a known offset from a part-center value.

TPM = Total Preventive Maintenance; regular planned review of all places and points where inspections can be taken

And measured evaluations for statistical data with corrections per OEM specifications.

OEM = Original Equipment Manufacturer; the first creator or designer of an item.

Nomenclature continued:

CAM = Computer Aided Manufacturing; use of the CAD model with manufacturing utilities, fixture design, coolant Nozzles, holding clamps, sacrificial plates, and transducer mounts.

CAD = Computer Aided Design: origin of the electronic definition [model] of the part to be designed.

Fixture = locates the part or item for a positional relationship of the cutting-tool and the machine-tool.

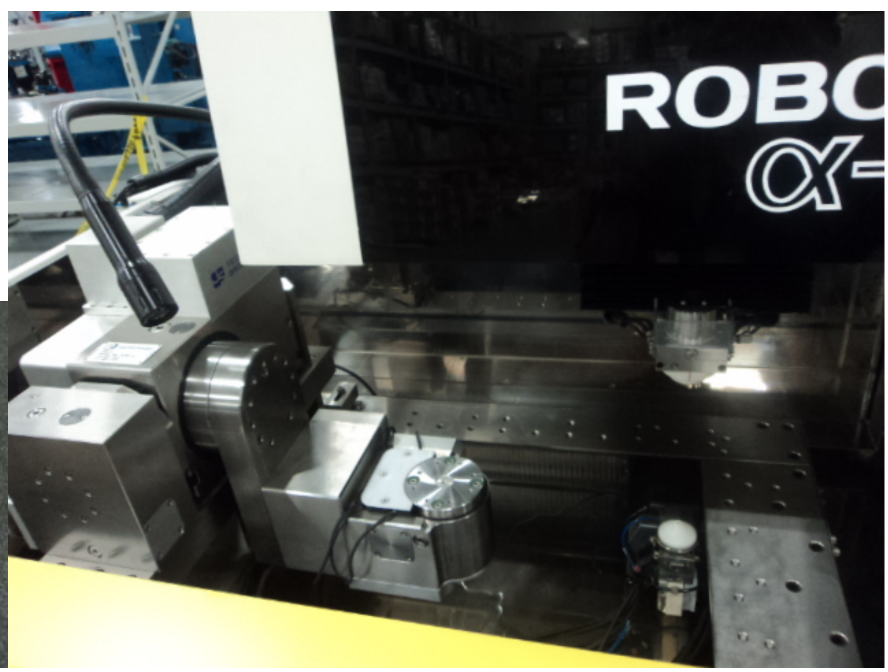
Slash-Angle = Angular component from the centerline of the disk, to the centerline of the slot.

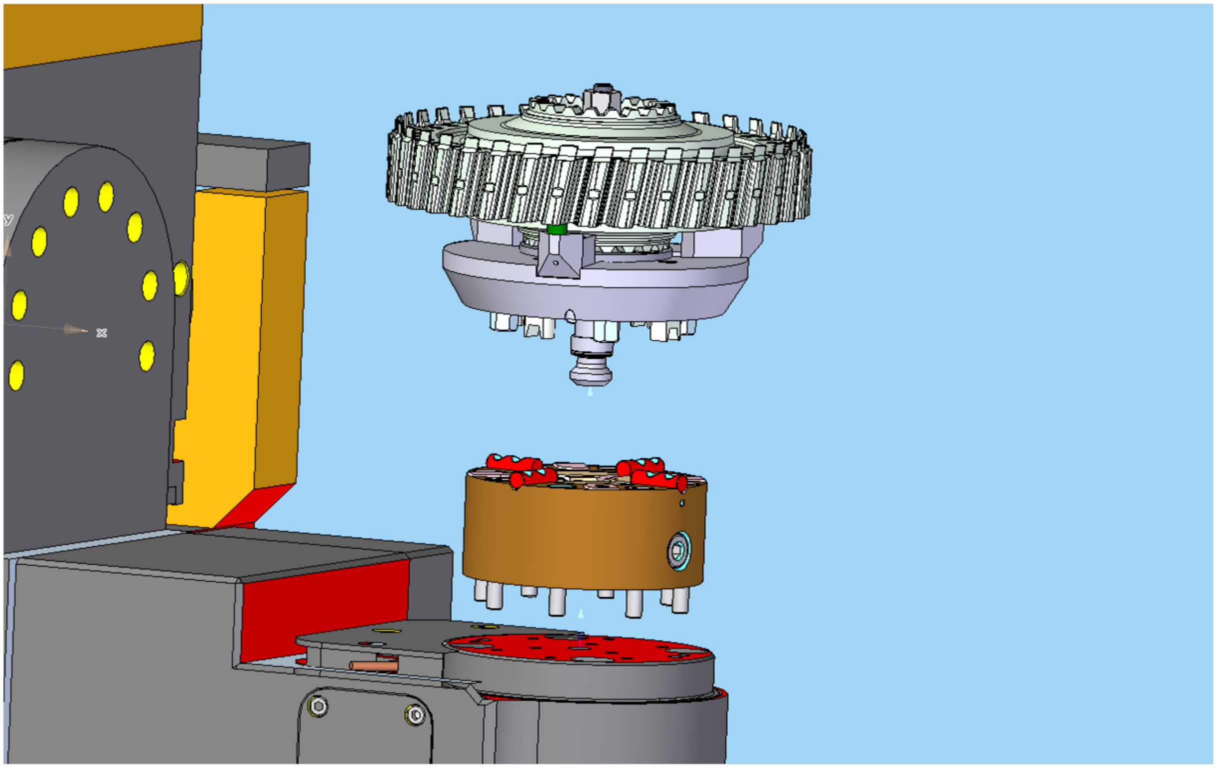
CMM = A **coordinate measuring machine** is a device for measuring the physical geometrical characteristics of an object, with a Touch Probe.

S-L = Structured Light; a 3D **scanning** device for measuring the three-dimensional shape of an object using projected light patterns and a camera, non contact. Needs electronic model of item for comparisons.

Research Methods:

This is a summary the manufacturing processes to produce the slots in the periphery of the turbine disk. Many of the shortfalls of broaching rotor slots can be overcome by wire EDM, with an internally linked tilt and rotary indexer. This is a stand-alone work center, only requiring electric power, tap water, compressed air, and a minimum 4 inch thick concrete floor foundation. Manufacturing must avoid placement near any large equipment that can transfer high shock or vibratory loads. The first step for manufacturing is the development of the multi-pass wire cutting computer program, with goals of creating consistent and conforming recast layer during cutting. The WEDM machine-tool manufacturer can train and guide the programmer, but the materials used for turbine disks require special power factors and slopes. A major factor for manufacturing to using WEDM is this ability to be programmed to machine these tough materials used for turbo machinery, with very little stress being introduced.





A common multi-pass program may take many nearly repeated cutter-path routings, with a variety of power settings, power slopes, current settings with unique on/off times. Because of the continuous fresh diameter of wire there is always cutting action taking place, but at a finer micro-amp rate from the previous pass.

That first-pass removes the bulk of the disk material, in starting to form the slot. The wire is advancing with nearly 180 degrees of engagement. This initial pass takes the longest cycle-time and leaves the thickest layer of recast. Excess disk material is programmed for the subsequently semi-finishing passes. For producibility gains, that first recast layer needs to be uniform to accurately preform the remaining passes. Flushing nozzles from both sides of the disk must push de-ionized water into the advancing wire's path. This advancing wire is very dependent on this flushing action, and is necessary to support the spark-gap throughout the thickness of the disk, with its slash-angle component. Hence both tips of the nozzles must be in close clearance to the part's surface, but never in contact.

The wire travels through the upper nozzle guides, through the disk, entering the lower nozzle guides, keeping the necessary tension on the wire, while it too is being eroded away. Here the programmer can speed the wire, which creates a fresh diameter for effective cutting. The main feature of the opposed flushing is to maintain uniform cutting from both sides of the disk, thus straightness. The spent particles are pushed away from the spark-gap, allowing the wire to advance. Later, these particles travel, and get deposited internal to the machine-tool in large filters that are monitored on the machine-tool's controller for their back-pressure. These factory back-pressure pre-sets protect the unit's pump, are alarmed. Back-pressure is also being monitored at the end of every pass, with the controller being capable to over-ride to finish a process-pass.

The subsequent pass (es), need to primarily address the remaining re-cast layer material, surface profile conformity, and surface finish improvements. With any remaining passes the machine-tool can often offer a micro polishing feature, just fresh wire-diameter [passing] with micro-ampere scrub, but very little cutting. The more modern W-EDM machine-tools, in using multi-passes can produce near zero recast layer thickness, where the user will struggle to find a measurement process to use for validations. With a extremely thin layer of remaining recast, chemical processes like electrolytic polishing can further reduce this remaining layer.

Chemical & Metallurgical Report [CMR] testing is used to evaluated both broached and WEDM notched Life Cycle fatigue (LCF) bars. Production plus CMR testing was evaluated on both broached and WEDM notched Life Cycle fatigue

(LCF) bars. With use of Striation counting of failed LCF bars being performed on both WEDM and broached bars to determine failure initiation. Data is gathered from a broaching work-center, and is compiled for actual slot costs including perishable tooling, man-hours, dimensional conformity [size, P-point & Spacing Error], control process manufacturing (CPM) validations, and cost of poor quality (COPQ).

Results of Findings of the Research: WEDM is a 6 sigma process, while Broaching is a 3 sigma process when considerations of the effects from sharp versus worn-edge cutting tools (not dull). Reviews of the expenses of MP-WEDM have been found to be approximately half the costs of broaching. With lifing results summarizing the LCF bars equal to, or better than broaching for IN718 based materials.

The MP-WEDM surface finish range is improved and narrowed over what broaching had been found to produce. With multi-pass there also exists the ability to add micro-finishing passes, with some cycle-time increases, for product enhancements, or improved dimensional control. To future demonstrate the flexibility that manufacturing can now have as an assets to the manufacturability of its products, instead of only what the process can deliver.

Today's modern WEDM machines can be easily programmed for the multi-pass processes, allowing for the removal of the recast thickness to consistent and acceptable limit. This lengthy time required for the WEDM process to perform, is mis-understood, being fully programmed allowing no operator support necessary during its processing, initially an operator is required only to load and unload the part and fixture. This lengthy production time compared to broaching, could be viewed as a drawback, but all the hourly rates should be complied and evenly spread over other WEDM machine-tools operating in a similar production mode. After a successful first-run part, one operator can overview many similar WEDM running operations. Vision an advanced WEDM cell having use of a robot-arm for the load/unload functions, with a revolving-operator only doing fixture set-ups and primary validations. Daily TPM would change-out filters or reload wire spools as required. Also the WEDM operator training necessary for the daily operation is minimal, with the machine-tool providing many status and text messages.

Main Conclusions and Recommendations: Multi-pass WEDM is a feasible alternative to broaching in rotating turbo machinery. Broaching has always been troubled with maintaining uniform distance between attachment slots. The capability of MP-WEDM has given manufacturing a method for addressing this issue. With the rotary axis, slits can quickly be made around the disk, relieve of the hoop type stress allowing a near stressless MP-WEDM operation. This feature is permanent in the cutting program and locked-out from operator altering.

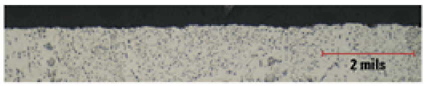
The vast inventory and human-support of perishable cutter segments used in broaching is no longer necessary. Large variability of the sharp versus dull broaches, and the remaining residual stresses in the disks are reduced by use of the MP-WEDM process. The extensive storage and maintenance of work-holding fixtures used in broaching are no longer required. With extensive broach and holding fixture designs no longer necessary, quicker testing can be accelerated by WEDM for program reviews, and customer milestones.

Major perishables for WEDM are the wire, its guides, flushing nozzles, resin bottles, and filters, being spread over numbers of disks, not just a few. WEDM set-up times are significantly less than broaching. With many features for set-up pre-programmed into the cutter program itself. In Summary design and product flexibility of turbo machinery is enhanced by the use of the multi-pass WEDM process.

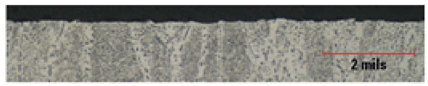
The wire EDM-machined Inconel components showed no measurable HAZ and no base-metal cracks. The maximum recast layer was less than 0.0009 inches and was practically non-existent (measuring 0.0001 inches) on the finishing pass. The Inconel components had a redeposited globular cluster measuring less than 0.0013 inches. See figure 3.

FIGURE 3: INCONEL, WIRE EDM TESTS

Inconel Sample	View	Max. Redeposit Globular Cluster	Max. Recast	Avg. Recast	Max. Recast Cracks	Max. BM Cracks	Predom. Heat Affected Zone	Hardness Test Location	HV_{300}
WEDM, 1 Pass	L	0.0013	0.0009	0.00024	0.0002	None	None	0.0025"	286
	T	0.0011	0.0007	0.00019	0.0002	None	None	Core	289
WEDM, 2 Pass	L	0.0006	0.0005	0.00006	0.0001	None	None	0.0025"	301
	T	0.0006	0.0005	0.00008	0.0001	None	None	Core	295
WEDM, 3 Pass	L	None	0.0002	0.00001	None	None	None	0.0025"	300
	T	None	0.0002	0.00002	None	None	None	Core	299
WEDM, w/gl.bead	L	None	0.0001	0.00000	None	None	None	0.0025"	280
	T	None	0.0001	<0.00001	None	None	None	Core	279



Inconel, Glass Bead Preparation WEDM



Inconel, WEDM

The wire EDM-machined stainless steel components produced no measurable HAZ or redeposited globular clusters and had an average recast layer less than 0.00022 inches. While recast and base-metal cracking was present, it was between 0.0004 and 0.0001 inches. In three-pass machining, virtually no base-metal cracks or recast cracks were present. See figure 4.

(*There is NO figure 4.)