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Evaluation of Advanced Wire-EDM Capabilities for the Manufacture of Fir Tree Slots in Inconel 718

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Abstract

This paper deals with a technological evaluation of wire electrode material and machining technologies for the production of fir tree slots by Wire-EDM to compete with the conventional broaching process. Meeting the high requirements on surface integrity and precision, new electrodes in combination with machining technologies have been developed in order to increase the productivity of this machining process. In particular three wire electrodes including a standard brass wire, a coated high-speed-cutting wire and a Ni-coated wire for zero contamination of Cu and Zn in combination with standard and specifically developed machining technologies for cutting Inconel 718 are presented. Evaluation criteria for the comparison are the demanding requirements on fir trees in turbine engine production like precision, surface roughness, minimization of white layer formation and contamination. Finally, an energy consumption analysis of the electrode/ machining technology combination is shown. The analyzed processes show that Wire-EDM is a capable process for the fir tree slot production.

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Keywords: Wire-EDM; Nickel Alloy; Surface Integrity; Electrode Material

1. Introduction

Safety critical aircraft jet engine components like turbine discs have to meet high demands in terms of surface integrity and geometrical accuracy. Most of the machined features in these components are produced by conventional manufacturing processes like milling, grinding or other cutting technologies.

Especially, the applied broaching process for the production of fir tree slots in discs is accepted to be a very critical manufacturing process. Although very high metal removal rates in combination with high surface qualities and accuracies can be achieved through this process, several crucial disadvantages must be accepted. High investment costs for the machine tools go along with large foot prints and high energy consumptions. Additionally, the tools to process the materials cause a high effort to substitute the broaching process. Long lead time from the order to the entry in operation of the tool, time consuming adjustments of the tool segments for an accurate production and high tool wear through the tough disc materials like nickel-based super alloys are some reasons for the mentioned effort. A detailed overview of the fir tree slot itself and the drawbacks of the production are given by Klocke et al. [1].

In the past, research work was carried out to develop an adequate manufacturing technology to replace the critical broaching process. An overview of substitution processes was given by Curtis et al [2] in the year 2008. In terms of Wire-EDM this survey concluded a capability as a pre-slotting manufacturing process. In the meantime analyzes were conducted to promote the Wire-EDM process as a manufacturing technology for the complete fir tree slot production from roughing to finishing. Surface integrity inspections were conducted of several Wire-EDMed aerospace super alloys.

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Nomenclature

Aj	Servo Reference Voltage / V
E	Consumed Energy / kWh
EPMA	Electron Probe Micro Analysis
HRC	Hardness – Rockwell Scale
Offs.	Offset / µm
P	Power / kW
PMC	Partial Mass Coverage / (µg/cm²)
Ra	Arithmetic Average Surface Roughness / µm
RC	Rough Cut
TC	Trim Cut
UTS	Ultimate Tensile Strength / (N/mm²)
$\dot{V}$	Volume Flow / (l/min)
d	Diameter / µm
f	Measuring Frequency / Hz
h	Work Piece Height / mm
l	Cutting Length / mm
l_t	Layer Thickness / nm
$\overline{l_t}$	Mean Layer Thickness / nm
p	Flushing Pressure / bar
$r_{min,inner}$	Minimal Inner Radius / mm
$r_{min,outer}$	Minimal Outer Radius / mm
t	Tolerance / µm
t_{man}	Manufacturing time for a single fir tree / min
t_r	Discharge Current Rise Time / µs
t_0	Pulse Interval Time / µs
$\hat{u}_i$	Open Voltage / V
w	Width / mm
κ	Specific conductivity / (µS/cm)

Newton et al. [3] investigated the effects of process parameters on the formation and characteristics of recast layer in Wire-EDM of Inconel 718. Due to decreased spark energy an improvement in terms of surface roughness values was observed. Micro hardness measurements showed a minor magnitude compared to the hardness of the bulk material, which was also detected by Li et al. [4]. The main effects on the recast layer thickness were the peak discharge current, current pulse duration and energy per spark. The average layer thickness was indicated between 5 and 9 µm. Through the usage of latest generator technologies and trim cut operations several publications documented a recast layer thickness near zero [1, 5-10]. Mainly analyzed workpiece materials in these studies were Ni- and Ti-based alloys. These materials were also used for studies on the behavior of Wire-EDM on the fatigue life by several researchers [7-9]. All of them concluded a comparable fatigue life in the same magnitude of specimen produced by grinding or milling compared to Wire-EDM. Beside surface integrity inspections an economic study was conducted by Antar et al. [10]. Due to the usage of copper-coated wires, an increase of 40% in the productivity of cutting Udimet 720 compared to standard brass wire production was examined. A complete Wire-EDM fir tree slot production in Inconel 718 was presented by Klocke et al. [1]. The introduction of a specific Wire-EDM surface integrity and precision requirement table was the basis for the evaluation of the produced slot. In both aspects the demands were met. The significant requirements were a contour within a tolerance band t = ± 5 µm, Ra < 0.8 µm and a near nil recast layer.

2. Experimental work

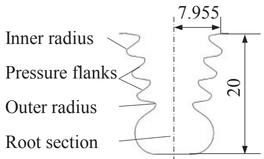
2.1. Workpiece material, test piece geometry and equipment

For the tests the aerospace alloy Inconel 718 was used. Several publications show the difficult-to-cut material properties and their effects on the machinability via cutting [11-13]. Table 1 shows a typical chemical composition of the nickel-based alloy [14]. The used solution treated and aged Inconel 718 is characterized by a coarse grain size which varies from 10 µm – 80 µm and possesses a hardness of 45 HRC.

Table 1: Inconel 718 composition

Element	Ni	Fe	Mo	Ti	Cr	C	Nb	Al
Weight %	Bal.	18.5	3	0.9	19	0.04	5.1	0.5

For the tests a generic fir tree slot geometry was designed (s. Figure 1, left). The designed slot has a depth d = 20 mm and a half width w = 7.955 mm. The minimal inner and outer radius is fixed to $r_{min,inner/outer}$ = 0.3 mm and the cutting length to produce the slot is l = 76 mm. The slot height was given by the available material to h = 40 mm.



Geometrical data	
Min. inner radius $r_{min,inner}$	0.3 mm
Min. outer radius $r_{min,outer}$	0.3 mm
Cutting length l	76 mm

Figure 1: Generic fir tree slot

As machine tool a GF AgieCharmilles 440 ccS was used. It is equipped with an anti-electrolysis 'clean cut' generator, which achieves best surfaces due to high-frequency energy-rich pulses. The power input of the machine tool was monitored with a power analyzer Chauvin Arnoux C.A 8335 QualiSTAR+. A sampling frequency f = 1 Hz was chosen. Surface roughness measurements of the test pieces were conducted with a Mahr MFW-250 measuring head. The measuring procedure was done in accordance to the specifications of the DIN EN ISO 4288. Precision checks were accomplished with an optical measuring device OGP Smart Scope ZIP 300. Finally, metallographic analysis in terms of contamination using EPM analysis and cross section views were prepared.

2.2. Wire electrodes and machining technologies

Three wire electrode types from the manufacturer Berkenhoff with diameter d = 250 µm were taken for the study (s. Figure 2). These are the standard brass wire electrode "Bercocut spezial" (BS), the coated high-speed wire electrode

"Topas plus X" (TPX) and the prototype wire "AGN3C" (AG). The design of the AG-wire contains a copper core, an inner β-phase layer for high material removal rates and an outer nickel-coating with the function to generate only such contamination which is already an element of Inconel 718.

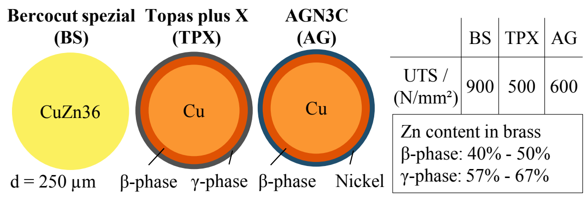


Figure 2: Wire electrode types for study

Preliminary tests with the BS- and the AG-wire were conducted to measure the wire electrode impact on the contamination of non-parent material into the surface. For this purpose straight cut tests were carried out. Available technologies from the machine tool library were chosen to achieve a final Ra < 0.8 µm. For the BS-wire the specific technology and for the AG-wire a standard TPX technology were applied. In Figure 3 EPMA line scans of the surfaces of both cuts are shown. A decreased thickness of the contaminated layer from $l_t \approx 85$ nm to $l_t \approx 17$ nm was achieved due to the usage of the AG-wire. The Partial Mass Coverage (following PMC) of both elements was drastically decreased for this wire, which results in $PMC_{CU} < 8\%$ and $PMC_{Zn} < 4\%$.

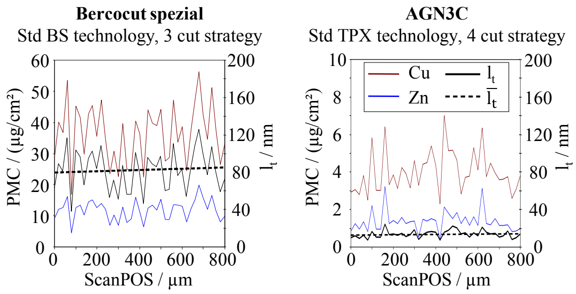


Figure 3: Contamination tests: BS-wire (left) vs. AG-wire (right)

Table 2 summarizes the main technology parameters of the survey. Five machining technologies were used. Technology 1 and 2 were used with the BS-wire, technology 3 as well as 4 with the TPX-wire and technology 5 with the AG-wire. The first and third technology in the table are standard technologies from the machine tool library for the machining of steel (technologies for cutting nickel-based alloys are not existing), both work with a 4 cut-strategy to meet the required demands in terms of surface roughness. The other three technologies were developed to achieve a productive and precise machining operation for Inconel 718 with the demand to meet the surface integrity requirements [1] – tolerance band t = ± 5 µm, Ra < 0.8 µm and a nil recast layer. The developed technology tables work with a corner strategy on the basis of the standard machine tool technology 1 for BS-wires. Each technology/wire combination declares a series in the survey. Following, the series number will be taken for the description and discussion of the results. All cuts were carried out in water-based dielectric with a specific conductivity κ = 15 (µS/cm). During all tests the flushing nozzles were sealed to the work piece surfaces. For the rough cuts the flushing pressure was set to 16 bar. For all trim cuts a volume flow of only $\dot{V}$ = 1 (l/min) was adjusted at the machine tool. The peak current of the rough cut discharges was in the magnitude of 200 A. With each technology/wire combination two fir tree slots were produced.

Table 2: Machining technology parameters

Tech./ Series	Mode	Shape	Offs. / mm	$\hat{u}_i$ / V	t_0 / µs	t_r / µs	Aj / V
1.BS	RC	Trapeze	0.227	80	6.0	0.70	49.0
standard	1.TC	Triangle	0.150	120	4.5	0.05	105.0
	2.TC	Triangle	0.139	60	14.0	0.05	38.3
	3.TC	HF-Mode	0.132	200	0.6	0.40	0.0
2.BS	RC	Trapeze	0.221	80	6.0	0.65	50.0
adapted	1.TC	Triangle	0.143	200	5.4	0.05	70.0
	2.TC	HF-Mode	0.134	200	0.6	0.40	0.0
3.TPX	RC	Trapeze	0.223	80	6.8	1.30	45.0
standard	1.TC	Triangle	0.155	120	5.4	0.05	122.0
	2.TC	Triangle	0.140	60	20.0	0.05	415.0
	3.TC	HF-Mode	0.131	200	5.0	0.40	0.0
4.TPX	RC	Trapeze	0.214	80	6.8	1.30	45.0
adapted	1.TC	Triangle	0.146	120	5.4	0.05	122.0
	2.TC	HF-Mode	0.134	200	5.0	0.40	0.0
5.AG	RC	Trapeze	0.219	80	8.0	1.40	43.0
adapted	1.TC	Triangle	0.140	200	5.4	0.05	70.0
	2.TC	HF-Mode	0.130	200	0.6	0.04	0.0

3. Results and discussion

In Figure 4 a single fir tree slot (series 2) of the overall 10 slots is shown exemplarily. The Wire-EDMed surface can be described as homogenous and flat without any visible process failures. On the wire entry and outlet corner a burr-free sharp edge is inspected. On the right side of Figure 4 the total manufacturing time including the rough and trim cuts for the production of one fir tree slot and the surface roughness in the root of the slot are presented. The test cuts of series 1 represent the highest cutting time $t_{man} \approx 60$ min. The highest productivity was achieved with the 3 cut-strategy and the TPX-wire (series 4). It was 33% faster than the standard BS-wire technology (series 1) and required $t_{man} \approx 40$ min. A decrease of manufacturing time can be analyzed comparing the standard 4 cut-strategies (series 1 and series 3) with the adapted 3 cut-strategies (series 2 and series 4). With the prototype AG-wire the production process of one fir tree slot required $t_{man} \approx 52$ min. For the series 1-3 a surface roughness value less than the required Ra = 0.8 µm was achieved. A slight deviation from the required value was measured for series 4 and series 5. Overall the BS wire electrode achieved the best mean surface roughness of Ra = 0.61 µm. It can be stated, that the technology adaptions (series 2 and 4) go along with a high increase in the productivity but a slight decrease in the surface roughness quality.

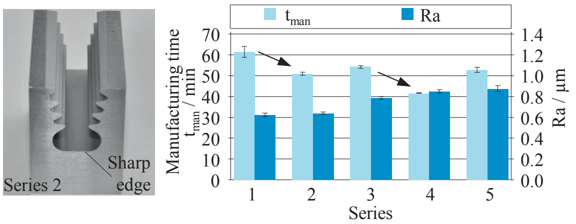
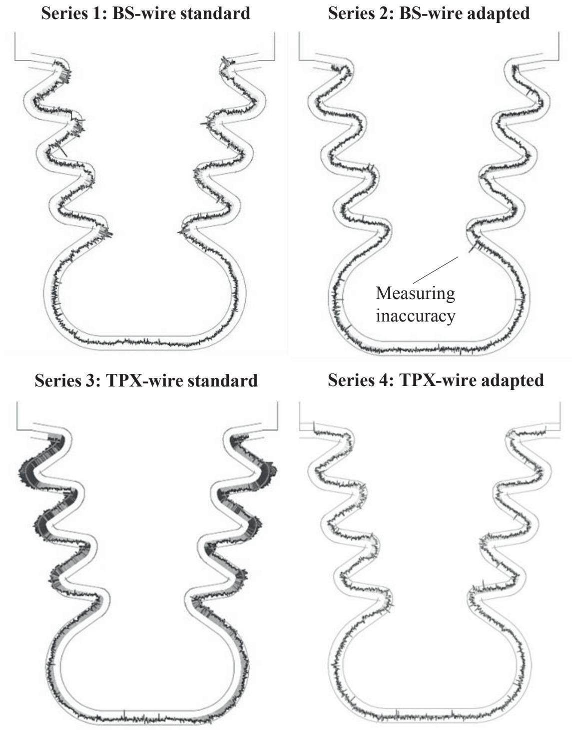


Figure 4: Wire-EDMed fir tree slot (left), manufacturing time and surface roughness vs series (right)

The single evaluation results of the accuracy measurements are illustrated in Figure 5. In comparison to series 1 and 3 (standard machine tool technologies) the new developed and adapted technologies 2, 4 and 5 feature an accurate and precise resulting contour. Measuring inaccuracies in the magnitude of few microns, which are characterized as random peaks in the measured contour, may appear through slight grime on the sharp edge of the geometry. An evaluation summary of the series is given in the table at the bottom of the figure.

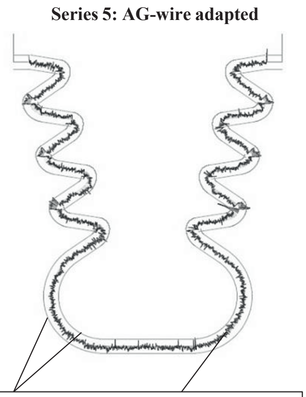
For series 1 and 3 the same tendencies were detected. In both technologies a wrong offset for cutting Inconel 718 is applied as the technologies are developed for the manufacturing of steel materials. This conclusion can be given through the perception that the measured contour predominantly is displaced to one side of the nominal contour. On the most important pressure flank (s. Figure 1; this flank establishes the force translation from the blade into the disc) nearly all series feature a good accuracy.

Cut outs of the fir trees' root sections were taken for rim zone inspections. The microscopy views are mapped in Figure 6. All surfaces feature a marginal recast layer. In all views no cracks through the layer into the parent material can be detected. Series 1 exhibits a near nil non-uniform white layer. The mean thickness of the layer is less than 1 µm. Overall the surface topography is flat. The surface of series 2 shows a more uniform constant white layer with the mean thickness near 1 µm. Compared to series 1 a minor magnitude of recast layer free regions is observed. The surface of series 3 shows the same characteristics as the one of series 2. A marginal difference in the topography formation can be observed. Series 3 has a slightly thicker and a marginal more cliffy structure. The surface which has been cut with the TPX-wire and the adapted technology (series 4) shows the thickest and the most inhomogeneous recast layer of all surfaces. On average it possesses a thickness of 3 µm and the topography features sharp edges. The Ni-coated wire (series 5) leaves a small and steady white layer on the surface. A mean thickness of 2 µm is detected. Overall a high quality surface integrity was observed. The best surfaces were produced with the BS-wire electrode.



Dim. accuracy	Series 1	2	3	4	5
Offset	-	+	-	+	+
Press. flank	-	+	-	+	+
Inner radius	-	+	-	+	+
Outer radius	-	+	-	-	+
Root	+	+	+	+	+

+: Within tolerance
-: Outside of tolerance



Similar for all measurments: Tolerance: t = ± 5 µm, measured contour

Figure 5: Accuracy measurements for the technology/ wire combination

In Figure 7 is the result of the energy consumption assessment presented. In the upper part of the figure a detailed graph of the series 3 and 4 is mapped. The power measurement can be divided in the single cuts. In the first part of the plot the alternating power measurement of the rough cut and in the rear part the flat measures of the trim cut can be seen. For the rough cut the mean power is P = 6 kW and for the trim cuts it is P = 3 kW. The main reason for the difference is the high-pressure flushing pump, which delivers in the rough cut a pressure of p = 16 bar. During the trim cuts a volume flow of only $\dot{V}$ = 1 (l/min) was adjusted. To provide this volume flow the pump consumed less energy than during the rough cut. The alternating behavior, which is more obvious in the plot of series 4, depends on the geometry strategy. The strategy minimizes the flushing pressure at sharp corners to secure the geometrical requirements. Each valley characterizes an inner or outer radius of the fir tree slot where the geometrical strategy is enabled to achieve the best accuracy. The difference between series 3 and 4 can be explained due to the fact that varied geometry strategies were used. For series 3 the strategy of the standard machine tool technology for TPX-wires and for series 4 the strategy of the standard BS-wire technology were applied. Through the awareness of this fact further potential to increase the productivity of series 4 was identified. At the bottom of Figure 7 the overall consumed energy of all series is shown. Series 1 consumed the highest energy E ≈ 4.3 kWh for cutting one fir tree. The minimal energy E ≈ 3 kWh was consumed by series 4.

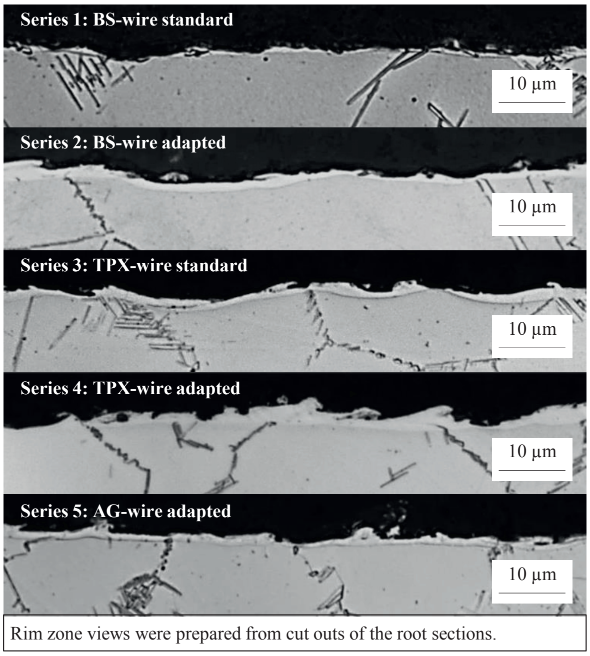


Figure 6: Rim zone views of all series

4. Conclusions

The conclusion of the evaluation of advanced Wire-EDM capabilities for the manufacture of fir tree slots in Inconel 718 are:

- Through the development of a nickel-coated wire the undesirable Cu and Zn contamination could be minimized. In terms of productivity and resulting surface integrity, the nickel-coated wire is comparable with the other tested wires.
- The productivities and accuracies of the developed 3 cut-strategies were increased compared to the standard machine tool library technologies. The increase did result in a slight degradation of the surface integrity.
- The best accuracies and surface integrities were achieved with the standard brass wire electrode. The requirements from the turbine industries in terms of surface roughness (Ra < 0.8) and accuracy (t = ± 5 µm) were met. In terms of recast layer a nearly layer free surface was achieved. Some concessions have to be made with the productivity.
- A decrease of the manufacturing time for a single fir tree slot by 33% was achieved through the usage of coated high-speed-cutting wire electrodes compared to standard brass wire electrodes. A further advancement could be achieved through the modification of the geometry strategy.

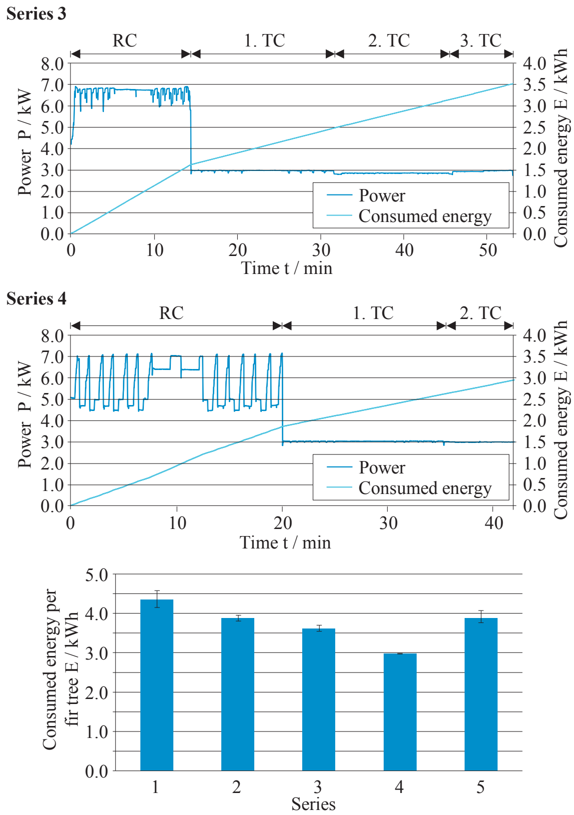


Figure 7: Detailed energy consumption of series 3 and 4 (top), overview of energy consumption (bottom)

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