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Efficient machining of complex-shaped seal slots for turbomachinery

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ABSTRACT

Complex sealing arrangement in turbomachinery can increase turbine efficiency by reducing leakage of high-pressure cooling flows into the hot gas path. While die-sinking EDM is widely used to machine straight seal slots, electrode preparation and wear make it less efficient for complex shapes. This paper presents research on optimisation of a variant of EDM milling using process control and fluid dynamics simulation to exploit optimal machining conditions. The analysis demonstrates a stable process to machine complex shaped slots by focusing on the key requirements for large-scale turbomachinery component manufacture, namely productivity, surface integrity and process monitoring.

1. Seal slots in turbomachinery

In turbomachinery, leakage of high-pressure cooling flows between adjacent turbine components (such as stator shrouds, nozzles, and diaphragms, inner shell casing components, and rotor components) into the hot gas path, also known as parasitic leakage leads to reduced efficiency or requires an increase in burn temperature [1]. Thus, turbine efficiency can be improved by reducing or eliminating leakage between the turbine components. Traditionally, leakage between turbine component junctions is treated with metallic seals positioned in the seal slots formed between the turbine components. Seal slots are deep narrow grooves made to accommodate a seal used to block or otherwise inhibit leakage through the junctions. Multiple spline seals are often positioned in axial and radial directions, in intersecting slots to reduce leakage. An example of a complex-shaped seal slot in nozzle guide vanes is presented in Fig. 1(a).

1.1. Seal slot machining

Machining of seal slots, pockets and grooves apart from drilling of cooling holes are the main areas for application of electrical discharge machining (EDM) in turbine manufacture [3], due to the obvious advantages of EDM over other more conventional processes where productivity is not limited by the hardness or strength of the workpiece and complex features, or high aspect ratio holes and cavities, can be readily machined.

Due to the required narrow deep geometry in difficult-to-cut materials, research in seal slot machining using die-sinking EDM particularly focuses on machining efficiency, tooling and surface integrity for different alloys such as Ti–6Al–4V [4], nickel-based superalloys [5] and g-TiAl [6]. Poor flushing or debris evacuation from high aspect ratio grooves deteriorate machining efficiency. A number of methods have been analysed for better debris evacuation such as ultrasonic assisted process [7] or special electrode designs [8]. For tooling, mainly graphite rib electrodes are used, where the type of graphite for high productivity is analysed in Ref. [9] and due to electrode wear, automated dressing of electrodes is analysed in Ref. [10].

In practice, some common requirements from the most engine manufacturers regarding seal slot machining are high productivity, surface integrity, automation and quality traceability. This is often achieved by modern die-sinking machines, where using dedicated fixtures and process control, seal slots are machined simultaneously in multiple workpieces to overcome the lower material removal rate (MRR) of EDM process. The requirement on geometric tolerances for seal slots is typically ±50 μm. While surface integrity protocols for EDM of aerospace components are confidential from engine manufacturers, generally, surface cracks extending beyond the re-solidified layer is unacceptable, whereas re-solidified layer thickness acceptance may vary from 10 μm to 50 μm. In terms of tooling, for complex-shaped slots as shown in Fig. 1(a), rib electrodes are either arranged using fixtures or electrodes can be machined, requiring additional setup time and costs.

In order to support the trend of increasing turbine efficiency through better sealing by the inclusion of complex-shaped seals and ecological machining, current paper presents an alternative method for seal slot machining in high-temperature alloys by combining EDM drilling for roughing and EDM milling for finishing operation. The proposed method is analysed by focusing on productivity and surface integrity, which are of primary interest for turbomachinery component manufacturing.

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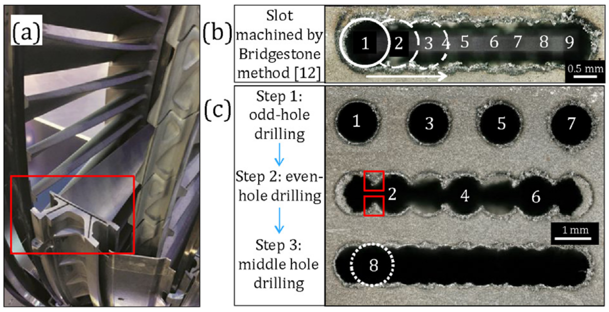

Fig. 1. (a) Seal slot with a complex shape in nozzle guide vanes [2]; (b) schematics of a slot machined in Inconel 718 using the Bridgestone method with overlapping holes and (c) a straight slot machined consisting of three distinct steps using the ODEM strategy described in Section 5.

2. Experimental setup and methods

2.1. EDM equipment and measurement methods

A 7-axis high-speed EDM drilling machine dedicated for aerospace applications (AgieCharmilles Drill 300) is used for experiments related to EDM drilling and milling. Deionised water is used as the dielectric. As tool electrodes, brass tubes with dimensions ø0.5 × 300 mm (single channel) and ø1 × 400 mm (multi-channel) are used. Inconel 718 is primarily used as workpiece material, whereas g-TiAl (TNM®-B1) and CMC (SiC-SiC) are used to demonstrate the process feasibility. Results from the modern die sinking machines (AgieCharmilles FORM – seal slot dedicated technology) are used as a reference for comparisons.

An optical microscope (Keyence VHX-5000 Series) with 100× magnification is used for imaging, whereas Alicona Infinitefocus microscope is used for optical 3D measurements. Talysurf from Taylor Hobson is used for surface roughness measurements. Surface integrity is analysed by polishing and etching the eroded samples, where re-solidified layer thickness and surface crack propagation is observed using optical microscopy.

2.2. Fluid dynamics simulations

Computational fluid dynamics (CFD) simulations are carried out using the commercial solver ANSYS 18.1. To investigate the lowest flow speed due to the pressure drop, a 400 mm long electrode is investigated. The length of the simulation geometry of the 1 mm diameter single-hole electrode is set to 100 mm to save computational power by reducing the mesh size. The inlet condition is defined according to measured data on the used EDM-machine, which supplies 65 bar by the dielectric fluid pump. Referring to the 100 mm long geometry, a pressure of 25 bar is calculated concerning the pressure drop. The gap between tool electrode and workpiece is set at 50 μm. Electrode wall and the wall of the workpiece hole are set to no-slip condition, whereas the wall of the workpiece is treated as a rough-wall with a sandstone roughness of Ra 5.36 μm according to surface measurement and employing the formula from Ref. [11]. The flow domain is limited by an opening boundary condition flush with the workpiece surface. The Reynolds number of the flow inside the 0.6 mm diameter cooling channel is calculated by $Re = (\rho \cdot d \cdot v)/\mu = 6700$ (slowest velocity of about v = 10 m/s, dynamic viscosity $\mu = 8.9 \cdot 10^{-4}$ kg/(m · s) and density of water of $\rho = 997$ kg/m^3). Thus, turbulent flow conditions can be assumed and taken care of by using the k-ε turbulence model. No thermal models are applied.

3. Comparison of different EDM strategies

3.1. Die-sinking vs. EDM milling

Since productivity is of a high importance for seal slot machining, a comparison between die-sinking EDM and layer-by-layer EDM milling strategy is performed for a straight slot in Inconel 718 with dimensions (W L H) 0.6 × 40 × 3 mm and final surface roughness Ra 3.2 μm. For the latter strategy, thickness of the layer is chosen as half of the electrode diameter 0.5 mm. In terms of erosion time, die-sinking EDM takes between 6–10 min depending on the chosen strategy between high speed to low electrode wear. On the other hand, after optimisation of process parameters to achieve a comparable geometric accuracy, EDM milling strategy results in a total machining time of 45–50 min. In order to reduce the machining time, an alternate milling strategy is analysed, termed here as EDM shaping. Here, a tube electrode is first fed towards the workpiece until the required slot depth is achieved, followed by machining in the lateral direction, i.e. electrode feed parallel to the slot length. Using this strategy, by applying electrode wear compensation, the slot is machined in about 30 min within the required geometric accuracy, which is still considerably higher than the observed die-sinking EDM performance. While EDM milling has obvious advantages over die-sinking EDM regarding electrode setup-cost and geometric flexibility, the machining time does not justify it as an alternative method for machining complex shaped seal slots.

3.2. EDM drilling for roughing

In order to utilise the above-mentioned benefits of EDM milling, an alternative method is found in [12], termed here as the Bridgestone method. Here, EDM drilling is performed for rough machining of a slot followed by EDM shaping for finishing to achieve the desired geometric accuracy and surface quality.

During roughing in the Bridgestone method, as shown in Fig. 1 (b), the first hole 1 is drilled into the workpiece, followed by drilling the holes 2–9 (termed overlapping holes) with some pitch/overlap to make an opening, thus forming a groove. With 40% overlap between the holes, rough machining time for the previously mentioned slot is about 10 min. Additional finishing using EDM shaping results in the total machining time of about 16 min, a considerable reduction compared to the EDM milling or EDM shaping, while preserving the advantages of the use of simple tube electrodes and flexibility to machine complex shapes.

4. Slot rough machining by EDM drilling

In order to further improve the efficiency of the roughing operation using EDM drilling, a hypothesis is presented and analysed using experimental analysis and fluid simulations.

4.1. EDM drilling conditions

In the Bridgestone method depicted in Fig. 1(b), hole 1 is machined in the full workpiece material, whereas the subsequent holes 2–9 only partially remove the diametrical material in the workpiece. It is proposed that EDM drilling efficiency for the hole 1 (termed odd hole) is higher compared to drilling the holes 2–9, mainly due to the electrode vibration resulting from sparking on only one side of the electrode and decrease in flushing efficiency in an open groove, as illustrated in Fig. 2(a, b). Additional drilling

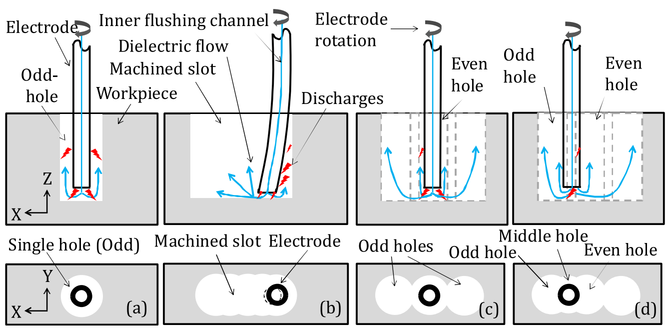

Fig. 2. Depiction of different EDM drilling conditions. (a) odd hole: drilling condition for hole 1 in Fig. 1(b); (b) overlapping hole: drilling condition in the Bridgestone method for the overlapping holes 2–9 in Fig. 1(b); (c) even hole: drilling condition for holes 2, 4, 6 in Fig. 1(c); and (d) middle hole: drilling condition for the hole 8 in Fig. 1(c).