A novel string-bead EDM mechanism for dressing of the conformal cooling channel fabricated by the SLM-additive manufacture

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Abstract. The conformal cooling channel (CCC) fabricated by the SLM method is a unique technology contributed to plastic molds by additive manufacture technology (AM). This paper proposes a novel electrical discharge machining (EDM) mechanism to trim the surface of the inner channel made of the selective laser melting (SLM -AM) and assembles a new string-bead tool, a guide-wheel set, a wire tension adjustment mechanism, and innovative electrode design. The experiments verify the EDM machinability and stability of the driving mechanism in the channel and investigate the feasible EDM parameters. As a result, this method can completely dress a 30mm straight channel with a diameter expansion of about 10%. This mechanism effectively trims the contour into a flat and even smooth tube and the taper to 38/30000, from the entrance to the exit. After EDM dressing, the surface roughness is reduced from the original 15-26 µm to 5.9 µm Ra. But some sort of bamboo-nuts overcutting occurred around the apex, due to the string tension and stumbling of tool electrode motion.

1. Introduction

In recent years, both mold flow analysis in plastic injection and metal laminate manufacturing developed rapidly. The conformal cooling runner geometry is designed based upon mold flow analysis and iteration simulation. However, it was not until combined with laminated metal additive manufacturing (AM) that the construction of conformal cooling channels (CCC) broke through the traditional processing. The metal AM lifts the limitation of the machining process.

In the past, in addition to the use of layered manufacturing to build the bent inner runner, some people relied on non-traditional processing technologies, such as EDM or ECM, to machine the bent inner runner, but their methods were all most aimed at the blind hole processing. This paper proposes a novel EDM process combined with a string-bead mechanism, aimed at the dressing of rough surface throughout the channel made by SLM laminated technology, but maintaining the dimensional accuracy of the runner profile.

In 1989, M. Fukui et al. [1] proposed a new type of EDM method to excavate bent track and called it Mole EDM. It is an electrode head equipped with a flexible mechanism to perform electrical discharging in the workpiece. The string mechanism is composed of the wire to take the tool electrode moving in bidirectional to proceed with the machining. They are manipulated to make EDM processing can be maintained as stable as possible for long-term machinability, and the dielectric fluid can circulate through the channel. In the beginning, they found that the inability to control the discharge gap and short circuit would cause processing difficulties. The author confirmed the feasibility of EDM to execute the channel EDM digging through three solutions. That’s by using a high-viscosity fluid, a high-speed rotating electrode, and using a servo mechanism to control the EDM discharge gap. Then, the curve with a small curvature can be processed smoothly, but the runner with large curvature is still restricted.

In 1999, Professor T. Ishida et al. [2] proposed a processing control called ADGC (Automatic Discharge Gap Controller) that combines a shape memory alloy (SMA) spring with a general compression spring and an electrode. The SMA spring is initially in the compressed state while the general spring is in released mode. When the current passes through the spring to increase the temperature, the general
spring is bounced and compressed. The result of the experiment shows that SMA springs controls the gap during the machining of curved channels, but it is usually limited to a two-dimensional runner.

In 2004, Professor Ishida [3] proposed a novel EDM mechanism equipped with electrode wheels and springs. The wire is used to control the direction of the electrode, and the spring is added to the electrode tip for the gap width control. The EDM mechanism is aimed at digging the curved runner. In the preliminary experiment, they used acrylic to make a quarter arc to test whether the mechanism can move along the channel, and confirm that the device moves smoothly in the arc curve. In the EDM process of the curve, the tool lift height, interval time, feed speed, processing depth, and other parameters are the same as the general EDM experiment. Their experiments confirmed the device can process long blind holes and maintains contour accuracy along the direction of the electrode. But, it is found that the debris cannot be efficiently expelled outward, and the device deviates from the route, which causes the diameter of the runner to change accordingly.

In 2015, Professor A. Okada [4] proposed a feasibility study on the curve channel EDM through the gravity suspension with a copper string-ball; the curved EDM of the suspension ball is characterized by (1) the direction of the suspension ball is always downward controlled by gravity, and (2) the workpiece is rotated to control the direction of the bent channel, (3) the machining stability is limited by the flow and slag discharge problems, and (4) the maximum depth is easily limited by the EDM stability. According to Okada’s reply to a speech in 2018, the problem of copper foil or copper wire and the workpiece is prone to contact. And the short circuit is solved by covering the power cord with an insulating material. The problem of rushing and slagging that limit stability, ultrasonic vibration was adopted in subsequent research to improve EDM stability and processing efficiency.

Since 2017, Professor A. Okada [5] further increased the ultrasonic vibration effect in the Z-axis direction of the workpiece in the gravity suspension copper ball curve EDM experiment to improve the short circuit and instability during deep hole processing. EDM experiments combined with ultrasonic waves to the gravity suspension copper ball can increase the processing depth and processing efficiency for the curve channel. Most of the past papers deal with the blind holes or channels, but the mechanism for throughout channels made by AM metal is still rare to see.

Up to 2019 and 2020, A. Okada’s team [6] proposed a fundamental study on internal space forming by EDM. This study proposes a new internal space machining method by EDM using a revolution ball linkage mechanism. This electrode consists of a vertical rotation rod fixed on the z-axis of the machine head, a tilting rod connecting to the lower rotation rod with a flexible hinge joint, and a copper tungsten ball electrode fixed to the lower end. The electrode in straight attitude is inserted into a small-diameter entrance hole, the material removal for internal space is performed by rotating the electrode. It was found that the angle can be well controlled by the revolution speed, indicating the ball can be positioned at precise positions, if the tilting rod length is changeable during the process. The EDM characteristics including surface roughness and electrode wear were investigated.

Therefore, this research proposes an innovative electrical discharge machining mechanism to dress the surface of the inner channel of the selective laser melting (SLM) mold and adopts a new string-bead mechanism, including a guide-wheel set, a wire tension adjustment mechanism, and an innovative tool electrode design.

2. Experimental principle and setup

During Electrical discharge machining (EDM) processes, the discharge produces high-temperature plasma between the tool electrode and the workpiece. Usually, both tool electrodes and workpiece are immersed into the dielectric fluid, and most of the fluid uses de-ion water or kerosene. EDM Discharge starts by applying a DC voltage pulse to the electrode’s ends. When motion control drives the tool electrode slowly approaching the workpiece within the discharge gap as close as ten to twenty microns, the voltage breaks down, and the plasma column rises to melt down the workpiece and remove the metal by spraying debris into machining fluid.
Metal laminated manufacturing processing is also called metal additive manufacturing (AM). By using computer-aided design to create a 3D image file and then using the slicing software to convert the 3D image file for the 3D printer. Moreover, this paper is focused on the material composed of metal powder, and the melting method adopts the selective laser beam. The printer stacks the materials layer by layer according to the path of the CAD file, and then, forms the solid object gradually. It is called the metal SLM process when the metal powder is adopted in the process, and it is especially promising in developing mold with conformal cooling channels (CCC).

2.1. Conception design of EDM dressing

Since the surface of the metal AM channel is rough and grows to irregular shape due to partial melting inherited in this stacking process. This research puts forward the idea of EDM dressing for the surface of curved CCCs. As shown in Figure 1, a wire and string-bead are adopted to guide shuttle-shaped electrodes, and small dashed lines connecting the shuttle electrode are to approach the curved arc pattern. The rough profile can be trimmed by a copper electrode guided by two segments of short lines L1 and L2. The other beads associated with the string tension provide supporting and maintaining the tool traveling direction. While the power core connecting the EDM spindle and the tool electrode aims at transmitting the discharge power.

Different from the previous research done by Fukui et al. which is to construct the net-shaped runner, this research adopts the bead string structure to guide the shuttle electrode to trim the surface of metal AM parts by EDM process. It is to reduce the surface roughness and maintain the profile accuracy of the flow channel. Compared with the previous mechanism in the past researches, the structure of the string-bead EDM tool expects a higher degree of freedom in turning along the CCC runners.

![Figure 1](image)

**Figure 1.** The conception of the novel string-bead EDM mechanism for dressing of the conformal cooling channel among the solid mold.

2.2. Mechanism of a closed-loop string-bead

On this experimental device, as shown in Figure 2, the original concept is to use the original tool lifting action of the CNC EDM machine, associated with the power cord to connect the shuttle electrode through the flow channel. The CNC-EDM is Mold-Master A430 built by a local vendor, YawJet Co, Ltd. Also, let the tensioned lead wire passes through to connect to the EDM spindle itself, and leading the shuttle electrode. The wheelset guides to form a closed loop to complete the trimming of the cooling channel. The upper machine head A is the fixed stationary column of the machine spindle, the upper head B is the movable part that moves along the Z-axis, and it is equipped with an EROWA chuck, connecting to the end of head B.

The power cord gets through the guide wheel D to reach the shuttle electrode. A leading wire connects the front end of the tool electrode to assemble a string-bead mechanism combined with plural beads,
which provides supporting and positioning. The leading wire reaches upward to the tension adjustor through the guide wheels set. As the EDM status gets unstable, the head B moves backward in the Z-direction make the string bead goes out of the working zone, and the tool electrode is also driven back through the guide wheelsets. After that, the upper head B moves downward again, and the string bead is moved back with the electrode shuttle to perform a stable electrical discharge machining continuously.

Figure 2. Setup and relationship of the string-bead mechanism with the spindle of the EDM machine.

Figure 3 reveals the CAD files of basic conformal channel specimens and their counterparts made by the EOS-290 system with AM-CORRAX metal powder. They include a straight conformal path, a 150 degrees obtuse corner channel, and a quarter of arc channel, respectively. The original surface roughness of these channels is ranged from Ra 15.4~26 µm. Because partially molten particles remain on the final SLM surface, the top roof of these channels possesses a typically rough profile like fluffy cotton.

Figure 3. The designed conformal channel specimen and their counterparts made by EOS-290 system.
The tool electrodes are designed to associate with various types of string-bead. As shown in Figure 4, all of the diameters of the tool beads are 10.0 mm, except the variant type of Figure 4(d), and namely the figure 4(e) with a smaller copper bead of 9.8 mm diameter. All the small bead balls and taper cones are made of UV-curing 3D-printer in the Lab, except rubber tapers and disks in figures (a)-(b) and the small hooks belonging to commercial fishing gears. Figure 4(a) reveals the typical length of the taper tool electrode is about 7.0 mm with a guideway and the inner thread. As shown on the right side of Figure 4(a), a fine shaft preserves a screw length of 2.0 mm for fastening the M4 screw. It can also be seen on the right side of Figure 4(c).

![Figure 4. EDM tool electrode associated with various types of supporting beads at both front and rear. (a) tapers type, (b) tapers-disks, (c) ball-taper-tool-ball, (d) ball-taper-tool-taper supporting bead, with diameter of the copper tool electrode of 10.0 mm. But another variant type (e) modified from (d) is done with a copper tool of 9.8 mm diameter.](image)

3. EDM and wire-tension investigation

3.1. EDM parameters survey

The preliminary tests are aimed at determining the feasible EDM parameters, stability of the novel EDM mechanism, and the effect of processing quality for the CCC surface.

(1) Open voltage (Vo): By using an oscilloscope, it is obvious to observe the discharge pulse trains at two open voltages. Some clusters of high-frequency short-circuit waves occur instantaneously at zero Volt window, as shown in Figure 5. It reveals that the open voltage of 120V has more stable and denser pulse trains than that of 200V, and there is almost no short-circuit clustering. Considering denser pulse trains correspond to higher removal efficiency and the more stable EDM status, therefore, an open voltage of 120V is adopted.

(2) EDM current (Ip): We use a 10mm long straight channel to evaluate the EDM current parameters. As shown in Table 1, although the 20A of Ip processing time is short, the surface roughness is not much different from that of the original AM parts. And after the 8A processing, surface roughness is the best among the three cases, but the much longer processing time (about 1.42 times that by 20A) does not meet the requirements. Finally, 16A of Ip is adopted as there are an intermediate roughness and total processing time.

(3) On-Time (Ton): Generally, the period of an EDM pulse cannot be deterministic controlled due to the ignition delay, but the discharge machining time (On-Time, Ton) is a set level for the pulse generator. As shown in Table 2, as the EDM Ton is set to the shortest 20.8 $\mu$s, the current cannot reach its peak value with enough rising time, which reduces the pulse energy and leads to a longer machining hour. When the Ton is set to 31 $\mu$s, there is a relatively normal and stable discharge pulse train. Its working hour is the shortest one among the three sets of parameters. Besides, the results of Table 2 reveal that the surface roughness conducted through these three sets is very close to each other. So, Ton = 31 $\mu$s is adopted. Since the other parameters are fixed to the default level, except servo voltage of 60V and the discharge Off-Time is pre-set as 18.1 $\mu$s in advance.
Figure 5. Investigation the response of open voltage (no-load voltage): (a) 120V, (b) 200V (CH1: Voltage from differential high voltage probe, CH2: Current from current probe).

Table 1. Effect of EDM peak current (Ip).

| Polarity (Workpiece) | Ip (A) | Machining Time (min) | Surf. Roughness Ra (µm) |
|----------------------|--------|----------------------|------------------------|
| Open Voltage Vo      | 120 V  | 8                    | 27                     | 4.365                  |
| Peak Current Ip      | 8, 16, 20 A | 16              | 21                     | 5.318                  |
| Ton: ON time         | 31 µs  | 20                   | 19                     | 8.5                    |
| Servo Voltage Vs     | 60 V   |                      |                        |                        |

Table 2. Effect of the feasible parameters on discharge On-Time (Ton).

| Polarity (Workpiece) | Ton (µs) | Machining Time (min) | Surf. Roughness Ra (µm) |
|----------------------|----------|----------------------|------------------------|
| Open Voltage Vo      | 120 V    | 20.8                 | 53                     | 5.025                  |
| Peak Current Ip      | 16 A     | 31                   | 21                     | 5.318                  |
| Ton: ON time         | 20.8,31,40 µs | 40             | 32                     | 5.572                  |
| Servo Voltage Vs     | 60 V     |                      |                        |                        |

(4) Servo voltage (Sv): Servo voltage is tested from 30 to 69V, and fixed the others according to previous tests. As shown in Table 3, processing time and surface roughness are the quality reference basis. Although the processing time is the shortest with 30V of servo voltage, its surface roughness output is the worst. Therefore, Sv=50 V is chosen as the servo voltage based on the compromise of roughness.

(5) Tool jump height & jump velocity: To perform efficient debris expelling from the working zone to make the EDM process stable, the EDM tool's periodical jumping is inevitable. Hence, the minimum jump height of 0.2 mm in this machine is adopted. In this experiment, the EDM provides a tool jump speed of 50~1000mm/min. In order to avoid the vibration of the string-bead and tool electrode, and to maintain the EDM process stable, the lowest tool jump speed of 50mm/min is selected.
### Table 3. Effect of feasible EDM servo voltage (Sv).

| Polarity (Workpiece)   | Sv (V) | Machining Time (min) | Surf. Roughness Ra (µm) |
|------------------------|--------|----------------------|-------------------------|
| Open Voltage Vo        | 120    | 30                   | 15                      | 7.997                    |
| Peak Current Ip        | 16     | 50                   | 21                      | 5.318                    |
| Ton: ON time           | 31 µs  | 69                   | 48                      | 5.658                    |
| Servo Voltage Vs       | 30, 50, 69 |                |                         |                          |

### 3.2. Wire-tension effect

For investigating the effect of wire tension, this study uses the Germany HANS SCHMIDT digital meter to evaluate the effect of string tension on processing time and surface roughness. First, it sets the thread tension to three levels, namely 1.0 daN, 1.5 daN, and 2.0 daN. As shown in Figure 6, due to its elastic property, when the wire tension reaches the peak value by the ratchet, it slowly falls to a lower steady-state level in a short time. Therefore, the peak tension needs to be set up to 25%-30% greater than the desired peak level, and then wait for the tension value to drop to the steady value before proceeding with the experiment. Therefore, an overshooting level seems required for the string tension.

Figure 6. Calibrate of the lead wire tension by about 30% overshooting.

Table 4 reveals that the electrode string with a tension value of 1.0 daN is relatively unstable during processing, resulting in greater surface roughness and longer processing time. While a tension level of 1.5 daN produces the best surface roughness and the shortest processing time. Therefore, the wire tension of 1.5 daN is chosen for better surface roughness and the shortest processing time.

### Table 4. The wire-tension level for the EDM trimming performance.

| Polarity (Workpiece)   | Wire-Tension (daN) | Machining Time (min) | Surf. Roughness Ra (µm) |
|------------------------|--------------------|----------------------|-------------------------|
| Open Voltage Vo        | 120                | 1.0                  | 64                      | 6.018                    |
| Peak Current Ip        | 16                 | 1.5                  | 21                      | 5.318                    |
| Ton: ON time           | 31 µs              | 2.0                  | 45                      | 5.968                    |
| Servo Voltage Vs       | 50 V               |                      |                         |                          |

### 4. EDM dressing results of cooling channels

#### 4.1. EDM dressing of the straight-channel
At the preliminary test with a short straight channel, the length of the straight-path channel is 30mm, the tool electrode chooses 9.8 mm diameter, and the EDM parameters are listed in Table 4. As shown in Figure 7, the bottom and top surface of the channel after dressing are revealed in figures 7(a)-(b), and the geometric relationship between the tool electrode and the surface of AM-parts is revealed in figure (c). During the long-term EDM hours, the wire tension is gradually adjusted to 2.0 daN to increase the stability of the electrode string.

As shown in Figure 7(c), the very rough fluffy-like surface of AM channel, especially at the top roof, is significantly improved due to the principle of EDM dressing. However, as shown in Figure 7(b), because of missing the central-line alignment of the electrode and the CCC channel, the EDM trimming mark remains at the very beginning entrance. Although the very rough surface of SLM-AM may not be finished at once by this single EDM dressing, the figures in 7(a)-(b) reveal the feasibility of processing.

As shown in Figure 8, the 30mm straight channel is further measured by the KEYENCE VT-5100 three-dimensional profile instrument to verify the inner surface of the CCC channel. The EDM processing direction is from right to left. As shown in Figure 8(a) inner diameter expansion is measured by scanning instrument, right arrow is at 5.0 mm from the entrance and similar to the exit measuring arrow. Figure (b) represents the profile of the bottom channel.

Figures 8. EDM dressing of a straight channel with 30 mm length, (a) inner diameter expansion from entrance to exit – top roof of the channel, (b) the profiles of bottom surface by KEYENCE VT-5100.

With five tests, channel diameters after EDM dressing are compared in Figure 9. And the entrance and exit differences of expansions on the inner diameter are listed in Table 5. Figures 9 (a)-(d) adopt the original diameter 10.0 mm tool. But in Figure 9(E), an electrode with a size of 9.8mm serves as the tool, so the channel did not reach the required 10mm. From Table 5, the diameter of the channel expands to 9.928mm at the EDM entrance, while 9.89mm at the exit. The diameter differences range from 38 to 850 µm. The smallest taper from the dressed channel is as low as 38/30000, which is obtained with the smaller tool.

Figure 9. Comparison on the channel diameters for five EDM trimming tests of straight channels.
Table 5. Channel diameter expansion after trimming, where test (E) conducted with 9.8 mm tool bead.

| Tests   | (A) | (B) | (C) | (D) | (E) |
|---------|-----|-----|-----|-----|-----|
| Entrance| 10.856 | 10.464 | 10.226 | 10.478 | 9.928 |
| Exit    | 10.02 (Un-finished) | 10.13 (Un-finished) | 10.116 | 9.858 | 9.89 |

Figure 10 reveals the comparison of the surface roughness for five trimming tests of straight channels. Tool electrodes with 10.0 mm diameter go through the test (A)-(D) perform quite uniform roughness for the surface, besides the bottom of tests (C) and (D). The abruptly risen roughness at the bottom reveals that there are partially machined surfaces remained in these tests. That’s because the wire tension always pushes the tool electrode moving upward to the roof. It also explains the reduction in expansion and deviation of channel diameters that occurred in figure 9 (C)-(D). However, the smaller tool electrode in test (E) results in a very rough top-roof because the supporting beads provide enough space for both the bottom and the roof surface, that only partially slight dressing is conducted by the EDM string.

In short, this EDM mechanism effectively trims the channel contour into a flat and even smoother profile. And the taper of the channel can be reduced to as small as 0.13%, with a smaller tool of 9.8 mm in compared with the design channel diameter. After this EDM dressing, the surface roughness is reduced from the original 26 µm to 5.9 µm Ra on the roof surface with a 10.0 mm tool. Furthermore, the diameters of the channel can further be precisely adjusted by tuning the EDM energy settings from EDM roughing to EDM finishing stages, besides the various tool bead diameters. That’s a very convenient way to meet the requirement of industrial needs.

Figure 10. Comparison on the surface roughness for five EDM trimming tests of straight channels.

4.2. Channel with the obtuse-angle corner

Because the bamboo nuts shape around the joint of the flow channel occurred at Spot S.4 of figures 11(c)-(d), that is introduced by some sort of beat motion and even vibration of tool beads. Since there is
always a wire tension to push the beads approaching the inner bank of the corner, it is clear that more supporting beads are required both at the front end and at the rear. As shown in Figure 11(a)-(b), the supporting beads around the EDM tool electrode in the proposed mechanism tend to wear out quickly and affect the machining path of tool. Besides the EDM conditions and the wire tension in Table 4, the support beads of this string EDM tool must be improved for the dressing of bent or arc channels. Therefore, a modified string structure with a bead-tool-bead type is proposed and implemented to improve the support in the rear of the tool, as shown in Figure 11(b). But combining the pushing tension in EDM feed-forward and backward of EDM jumping cycle still results in such a beat motion and even stumbling of the tool beads.

As shown in Figure 11(c)-(d), the expansion of the channel of the obtuse-channel after EDM is compared at four spots along the cross-section. Each arrow represents the scanning path and the direction of the 3D-profile instrument. The inner diameters around the obtuse-angle channel after trimming are listed in Table 6. The diameters at S.1 and S.4 are larger than the other two spots because of the entrance and exit positions, respectively. But, at the region around S.2 and S.3 for both top roof and bottom, it reveals a more uniform diameter and better surface integrity due to stable EDM trimming. Better surface roughness is also expected due to the stable string driving and tool motion.

![Figure 11. Morphology and expansion of the obtuse-channel after EDM trimming. (a) original type tool, (b) modified bead-tool-bead tool string, (c) top roof and (d) bottom surface.](image)

| Spots | Diameter (mm) @Top Roof | Diameter (mm) @Bottom |
|-------|--------------------------|-----------------------|
| S.1   | 12.07                    | 11.21                 |
| S.2   | 11.51                    | 11.54                 |
| S.3   | 10.87                    | 10.97                 |
| S.4   | 12.54                    | 12.46                 |

The straightness and uniformity of a channel are further compared by the Keyence profile scanner along the central line of axial direction. As shown in region 1 of Figure 12, both top-roof and bottom reveal the effect of bamboo nuts shape. Notice that the depth scale is different for these two regions. As shown in region 2 of Figure 12, the typical roughness results from partially molten particles at the top-roof in Figure 12(c), and some deeper caves occurred at the bottom surface due to the bead vibrating digging into the AM-part. However, although a modified string tool electrode is proposed, that the copper tool can’t turn over smoothly because the curvature at the corner apex exceeds the string-bead capability. Which verifies the proposed string-bead EDM mechanism cannot finish the trimming task for a bent obtuse corner.
Figure 12. Comparison of straightness along axial direction of obtuse channel after trimming (a) top-roof and (b) bottom surface by EDM, and along the trimming region, respectively.

5. Conclusion
In this paper, a novel string-bead EDM mechanism is proposed and EDM operation parameters are investigated for the dressing of cooling channels fabricated by SLM additive manufacture. For the straight channel with 30.0 mm length; The inner diameters after 5 tests range from 9.86 - 10.48 mm with 10.0 tool, and 9.89 - 9.93 mm with 9.8 mm tool bead. The diameter expansion of the finished channel can be adjusted further by processes planning. The minimum taper error by EDM trimming is 38/30000 at 30.0 mm length. The best surface roughness is Ra 5.9 µm at the bottom surface. For the obtuse corner channel; The inner diameters range from 10.868 - 12.546 mm. The best surface roughness is Ra 6.86 µm. But some sort of bamboo-nuts overcutting occurred around the apex, due to the string tension and stumbling of tool electrode motion. In future studies, a more sophisticated mechanism to cope with the problem of wire tension and to provide firm support for the tool electrode is on the going. Moreover, to make a smooth turning at the corner apex, the specimen will be designed with a round chamfer.

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