Influence of EDM generator programs on shape and surface roughness of Ni-Ti sheets

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Abstract. In the last decades caloric cooling technologies received an increasing scientific and industrial interest as promising alternatives to conventional vapor compression technology. Theoretically, efficiency of caloric technologies is more than 40% higher than for the conventional vapor compression cycle. Particularly interesting is elastocaloric cooling, which is an emerging technology, occurring due to the uniaxial mechanical loading of active regenerators. These are made of shape memory alloys, such as Ni-Ti. The regenerators must have a high fatigue resistance to withstand multiple loading cycles and simultaneously possess excellent elastocaloric properties. Therefore, it is crucial to establish a manufacturing process that allows fabricating thin regenerator elements with profound surface quality and as little impact on their functionality as possible. Considering the challenges of conventional machining technologies due to the specific characteristics of Ni-Ti, electrical discharge machining (EDM) demonstrates a high potential to meet the requirements for micro-shaping surfaces for elastocaloric applications. This paper presents fundamental analyses of the influence of EDM generator programs on the resulting removal depth, removal width and surface roughness of Ni-Ti sheets. Based on the perspective application in elastocaloric applications, adequate EDM programs are selected with regard to the targeted precision, surface roughness and minimal surface roughness.

1. Introduction and fundamentals of elastocaloric cooling

Around 8.5% of the globally consumed electricity in 2019 was used for the space cooling, which is also responsible for about 1 Gt of CO₂ emissions in that year [1]. The European Union set a clear target to become a first climate neutral continent by 2050 [2]. In order to achieve this goal, it is necessary to improve cooling and refrigeration technologies, so that environmentally hazardous substances would be completely phased out from the usage and at the same time an energy efficient way for cooling and refrigeration would be provided. Therefore, it is necessary to develop not-in-kind cooling technologies that would be environmentally friendly alternatives to conventional vapor compression (CVC) technology. One of such technologies is elastocaloric cooling, which was listed as one of the promising alternatives to CVC [3]. This is because, theoretical second law efficiency of caloric technologies can reach more than 60%, while for the small-scale appliances using the vapour compression technology it is generally below 20% [4,5]. Moreover, the hazardous gases are eliminated from the cooling cycle, since the active material is a solid matrix, which responses to the applied
external stimuli by creating a cooling effect [6,7]. The heat transfer fluid is water or water-based solution of corrosion inhibitors.

Elastocaloric cooling is driven by the elastocaloric effect (eCE), which is a property of a material to produce heat under an external uniaxial stress [8,9]. The magnitude of a caloric effect in a certain material is quantified by the isothermal entropy change and the adiabatic temperature change [8,10,11]. The eCE is found in polymers, such as natural rubber, and shape memory alloys (SMA) such as the near-equatomic Ni-Ti [8,10]. In order to obtain the elastocaloric effect, stress induced transformation is required. When SMA in the austenitic phase is loaded, at the critical stress the transformation to the martensitic phase begins until the de-twinned phase is reached [10]. When unloaded, the material returns to its original, austenitic state. The transformation from the austenitic to the martensitic phase causes heat generation, while reverse transformation forces the material to absorb heat from the surroundings [10].

The eCE is a reversible process, even though, hysteresis is associated to both transformations. Nevertheless, the eCE can be used for cooling and / or heat pumping applications, when a regenerative thermodynamic cycle is exploited to build up a temperature span between the heat source and the heat sink. In order to achieve this, a regenerator, which is a structure with high surface to volume ratio made of an elastocaloric material (eCM), must undergo multiple tension / compression cycles. Figure 1 shows a sketch of a double corrugated plate which was designed for perspective use as a part of an active elastocaloric regenerator [12,13].

![Figure 1. A differential volume of a double corrugated regenerator plate for elastocaloric applications.](image)

Due to the high stresses and strains that must be applied to achieve the phase transformation and exploit the eCE, fatigue resistance of the active materials becomes an issue limiting their functionality. The life time of the constructed regenerators strongly depends on their surface roughness and the selected machining methods [14]. Thus, it is very important to find a suitable machining process and parameters in order to produce fully functional and mechanically stable regenerators.

Since mechanical machining of the thin Ni-Ti sheets is challenging due to the reduced mechanical stability of the sheets, electrical discharge machining (EDM) offers a high potential for structuring the regenerator-plates and controlling their resulting fatigue resistance due to its ablation mechanism. The challenge is to find applicable machining parameters that do not affect the material’s functional properties too negatively.

2. Fundamental influences of EDM on the material properties of Ni-Ti

Ni-Ti is an excellent SMA and it is widely applied in biomedical and engineering fields for manufacturing bone implants, actuators, chevrons [4], which all require high surface quality. It was demonstrated that the functionality of Ni-Ti is highly affected by machining methods [15,16] and fabrication routines. The structural fatigue of Ni-Ti is influenced by chemical impurities with oxides and carbides when manufacturing thin films [7,8] or porous Ni-Ti structures and formation of heat-affected zones (HAZ) when using laser cutting or high discharge energy in EDM [16]. These chemical impurities not only affect the temperature at which the direct and reverse phase transition takes place, but also act as crack nucleation sites [4]. These cracks can lead to the failure of the material.
Moreover, the stress distribution is non-uniform in the machined areas compared to the base workpiece material, resulting in different mechanical properties within the active material. For example, the resistance to tensile or compressive stress is reduced at the machined areas [16], which lead to more rapid cold deformation. Once this state is reached, the material is permanently disabled. According to the current state of the art, EDM offers the possibility for high-precision surface structuring, without significant change of the material’s properties in the near of the outer surface. Recent researches focused on micro-EDM of Ni-Ti by investigating electrical and non-electrical machining parameters. It can be derived that an increase in discharge energy increases material removal rate (MRR) but also tool wear rate (TWR) and surface roughness (SR). Increasing capacitance [17–21], pulse current[20,22–24], pulse on time [20,22,23] gap voltage [17,18] and discharge voltage [19,21] were all found to increase discharge energy. Melting temperature and thermal conductivity are the most significant workpiece material related, non-electrical parameters [19,23] since an increase of one or both results in lower removal rate and higher tool wear.

The discharge energy is the parameter with most influence on the HAZ, where mechanical properties and microstructure are affected by the heat of the machining process [25]. This results in mechanical properties that differ from the unaffected basic material. By applying a controlled, low discharge pulse energy and thus targeted reduction of the thickness of HAZ, machining of complex micro-geometries in Ni-Ti with high surface integrity and low surface roughness down to Ra = 0.1 μm were realized [26–28]. Differential scanning calorimetry (DSC) results of micro-EDMed samples revealed that by applying discharge pulse energies lower than 10 μJ, it is possible to realize only negligible thermal influences [22,29].

3. Experiments

Even if the state-of-the-art indicates that micro-EDM has the potential to machine Ni-Ti with high precision and high surface quality, the process continues to face challenges related to too high thermal damages on the machined surfaces. When reducing discharge energy, a low MRR and a high TWR are expected, which represent significant hindrances for machining the required regenerator part surfaces. As a result, there is a lack of knowledge about how the machining process must be designed to reduce inefficient discharges and thus reduce the thermal damage. In addition, the special geometry of the regenerators, as shown in Figure 1, requires additional demands on the process regarding the design of the clamping system and the support of dielectric. For this reason, experiments were carried out to determine the basic machinability of a Ni-Ti sheet with available erosion programs. Fundamental analyses of the influence of the chosen EDM generator programs on the resulting shape of the removals, the surface roughness as well as the material removal rate and the tool wear rate were carried out.

3.1. Experimental setup

The experimental analyses were planned for a ZK genius 700 sinking EDM machine from Zimmer & Kreim GmbH (Breinbach, Germany). This system allows simultaneous 4-axes machining with a positioning accuracy of ± 1 μm for the linear stages and ± 0.001 ° for the rotational C-axis [30]. The machining experiments were carried out in a bath of EDM oil of the type Ionoplus IME-MH from Oelheld GmbH (Stuttgart, Germany).

For the determination of the basic machinability of Ni-Ti, linear one-axis sinking experiments in Z-direction were carried out using electrode rods made of copper with a diameter of 5.0 mm. A Ni-Ti sheet from Memry Corporation, USA, with the dimensions of 39.0 x 50.0 x 0.6 mm³ was used as workpiece. X-ray fluorescence analysis was carried out to characterize the chemical composition of the alloy. The results indicate atomic contents of 50.5 at% Ni and 49.5 at% Ti.

Figure 2 shows a photograph of the machining setup, implemented in the sinking EDM machine. The copper tool electrode is clamped in a collet and fixed on the Z-axis of the EDM-machine using a zero-point clamping system. The Ni-Ti sheet is fixed in a standard workpiece clamping system, which is mounted on the machine table.
Figure 2. Photograph of the tool electrode and the Ni-Ti workpiece implemented in the sinking EDM machine.

3.2. Design of experiments
To analyze the basic machinability of Ni-Ti, the three generator programs named Cu-Ti 30-30, Cu-Ti 15-15 and Cu-Ti 9-9 were selected. The respective discharge parameters, which are accessible via the machine tool’s database, are carted in Table 1.

Table 1. EDM processing parameters.

| Generator program | VDI class | $U_{\text{ign}}$ [V] | $U_{\text{oc}}$ [V] | $T_{\text{on}}$ [ms] | $T_{\text{off}}$ [ms] | C [nF] |
|-------------------|-----------|----------------------|---------------------|---------------------|---------------------|-------|
| Cu-Ti 9-9         | 9         | 150                  | 140                 | 8                   | 12                  | 1     |
| Cu-Ti 15-15       | 15        | 150                  | 140                 | 20                  | 20                  | 10    |
| Cu-Ti 30-30       | 30        | 270                  | 260                 | 50                  | 100                 | 6100  |

The three available generator programs had been designed for machining TiAl6V4 by the manufacturer of the machine tool. All the chosen programs use an iso-pulse generator and positive tool polarity. They differ in terms of ignition voltage ($U_{\text{ign}}$), open-circuit voltage ($U_{\text{oc}}$), discharge pulse duration ($T_{\text{on}}$) and pause times between the discharge pulses ($T_{\text{off}}$) as well as capacitance (C). This results in different discharge energies. Hence, different targeted surface roughness according to VDI 3400 classification [31] are specified by the last number of the respective program names. In this context, the program Cu-Ti 30-30 provides the highest discharge energy and consequently the highest surface roughness to be expected.

The target depth of each removal was set to 0.2 mm, which almost corresponds to the amplitude of the corrugation presented in Figure 1. In order to ensure a constant initial state, the electrode was dressed after each machining experiment. To assure the exchange of dielectric in the working gap, the immersed flushing of the dielectric bath was assisted by flushing strokes of the Z-axis. The effective removal time between the single flushing strokes was set to 1 s.

4. Results
For the qualitative and quantitative analyses of the erosion results, images of the removals were captured and measured with a Keyence VK-9700 laser scanning microscope (Osaka, Japan). The measurement results were evaluated with Mountains Map® analysis software. The diameter $D$, the removal depth $T$ and the surface roughness values $S_a$ and $S_z$ were determined. For the determination
of $D$, $T$, $Sa$ and $Sz$ the measurements were repeated 3 times on different measuring areas and the mean value and the standard deviation were calculated. In addition, the length of the electrode wear $W_l$ was derived and the material removal rate $MRR$ was calculated according to Equation 1, where $V_Z$ represents the volume of a cylindrical removal and $t$ the machining time.

$$MRR = \frac{V_Z}{t} = \frac{\pi}{4} \frac{D^2 T}{t}$$

### 4.1. Microscopic characterization

Figure 3 shows top view images of the removal results realized with the three chosen generator programs.

![Top view images of the erosions realized with the chosen EDM programs.](image)

As can be seen, the machining was successful with all three generator programs. The removal in Figure 3a) appears more uneven than the removals in Figures 3b) and 3c), which appear comparable to one another. Nevertheless, a lower roughness is expected for the removal in Figure 3c). However, both erosions machined with Cu-Ti 15-15 and Cu-Ti 9-9 show erratic deepened structures in the center of the removal area, which are caused by undesired discharges due to poor flushing conditions. This indicates that the flushing strategy needs to be adapted to achieve a sufficiently high precision for the prospective machining of the regenerator shapes. Detailed views of the removal results are shown in Figure 4.

![Microscope images of the erosions realized with the chosen generator programs, magnification: 50 x.](image)

There are significant differences in terms of the resulting surface quality. While a very rough surface was created with Cu-Ti 30-30, the surface quality with Cu-Ti 15-15 and Cu-Ti 9-9 is significantly increased. The resulting surface with Cu-Ti 30-30 is shown in Figure 4 a). Due to the high discharge energy, discharge craters with lateral dimensions around 150 µm are recognizable. As highlighted by
the red arrows, the surface is characterized by cracks that result from high discharge energy and thermal stress. Thus, Cu-Ti 30-30 is not suitable for machining Ni-Ti for elastocaloric applications, since it is expectable that the fatigue strength will be exceeded too quickly. At lower discharge energies machined with Cu-Ti 15-15 (Figure 4 b) and Cu-Ti 9-9 (Figure 4 c) no cracks were detected. The average lateral dimensions of the single discharge craters were determined to be 15 µm for Cu-Ti 15-15 and 9 µm for Cu-Ti 9-9, respectively. Thus, these generator programs are more applicable for machining Ni-Ti for eCE-regenerators.

4.2. Analyses of shape and surface roughness

The experimental results were evaluated by calculating the aerial roughness values with MountainsMap® analysis software. Figure 5 shows the resulting arithmetical mean height $S_a$ and Figure 6 the maximum height $S_z$ achieved with the used generator programs as bar charts.

![Figure 5. Arithmetical mean height $S_a$ achieved with the three EDM generator programs.](image1)

![Figure 6. Maximum height $S_z$ achieved with the three EDM generator programs.](image2)

The highest roughness values of $S_a = 3.01 \pm 0.07$ µm and $S_z = 136.1 \pm 49.4$ µm were measured for Cu-Ti 30-30 as expected from the qualitative inspection. Here, the standard deviation of 49.4 µm for $S_z$ is comparatively high due to the large size of the discharge craters. The lowest roughness values of $S_a = 0.49 \pm 0.11$ µm and of $S_z = 7.88 \pm 0.88$ µm were achieved with the generator program Cu-Ti 9-9. However, the targeted roughness values according to VDI 3400 [32], which are shown in Table 2, were not achieved for all eroding-programs except for $S_a$ using Cu-Ti 30-30. This is due to the material characteristics of the Ni-Ti workpiece, which differ in terms of melting temperature and thermal conductivity from TiAl6V4, for which these generator programs were designed.

| Surface classification according to VDI 3400 [31]. |
|------------------|------------------|------------------|
|                  | VDI 30           | VDI 15           | VDI 9            |
| $S_a$ [µm]       | 3.21             | 0.56             | 0.28             |
| $S_z$ [µm]       | 11.7 – 15.8      | 2.2 – 3.7        | 1.3 – 2.2        |

The resulting diameters $D$ were measured on the bottom of the single removals. The results are shown in the bar chart of Figure 7, where the error bars highlight the calculated deviations of single measurement values.
Figure 7. Removal diameter $D$ on the bottom of the removals realized with the three EDM generator programs.

All removal diameters are narrower than the diameter of the used electrode, which exhibits 5.0 mm. This is caused by the process-related circumferential wear on the tool electrode. The largest diameter of $(4.994 \pm 0.080)$ mm was achieved with the generator program Cu-Ti 15-15. This means that the circumferential tool wear was the lowest. The highest circumferential tool wear occurred with Cu-Ti 30-30, where a diameter of $(4.667 \pm 0.043)$ mm was measured.

The measured removal depths $T$ are shown in Figure 8 and the corresponding tool wear lengths $W_l$ can be seen in Figure 9. The error bars represent the measured $S_z$ values of figure 6, which illustrates the deviation of the surface peaks and valleys from the measured values.

Figure 8. Removal depth $T$ realized with the three EDM generator programs

Figure 9. Tool wear length $W_l$ realized with the three EDM generator programs

With the generator program Cu-Ti 15-15 the maximum depth $T$ of 188 $\mu$m was realized, which represents the slightest deviation from the targeted depth of 200 $\mu$m as highlighted by the dashed horizontal line. Correspondingly, the lowest tool wear length $W_l$ of 12 $\mu$m was detected for this program. In contrast, the smallest depth of 84 $\mu$m along with the highest tool wear length of 116 $\mu$m were measured with the generator program Cu-Ti 30-30. Hence, regarding the removal accuracy and the wear behavior, Cu-Ti 15-15 represents the best choice of the selected generator programs for machining Ni-Ti.
4.3. Analysis of the material removal rate

The material removal rates MRR were calculated based on the results of the removal diameter and the removal depth as well as under consideration of the machining time of the three generator programs. The measured machining times were 0.2 min for Cu-Ti 30-30, 45.0 min for Cu-Ti 9-9 and 105.0 min for Cu-Ti 15-15. The resulting MRR are shown in Figure 10.

![Figure 10](image_url)

**Figure 10.** Material removal rate MRR realized with the three EDM generator programs.

The maximum and minimum values were calculated according to the deviations described for the removal depth (Figure 8) and diameter (Figure 7). For a useful comparison of the strongly deviating results, the bar chart includes two interruptions within the value ranges (0.08…1.32) mm³/min and (1.37…13.22) mm³/min. These interruptions were chosen, because the average MRR of 7.18 mm³/min achieved with Cu-Ti 30-30 is significantly higher than the average MRR of 0.06 mm³/min achieved with Cu-Ti 9-9 and the lowest average MRR of 0.04 mm³/min achieved with Cu-Ti 15-15. These deviations are caused by the significantly differing discharge energies, which on the one hand results in significantly more material removal volume per time with Cu-Ti 30-30 but on the other hand also causes high tool wear. The high tool wear rate and the large deviations detected for this generator program reveal that Cu-Ti 30-30 is not suitable for precise machining of components for elastocaloric applications. However, the programs Cu-Ti 15-15 and Cu-Ti 9-9 offer the potential for processing such elements.

5. Summary and conclusion

For the topic component manufacturing of elastocaloric applications apart from the actual state of the art, the influence of available sinking EDM generator programs on the resulting removals of Ni-Ti was presented. Experiments were carried out with a commercially available setup. The applicability of three generator programs was examined regarding their fundamental applicability for machining a Ni-Ti sheet. The resulting removal widths, removal depths and surface roughness values $S\alpha$ and $S\epsilon$ were analyzed. Furthermore, the tool wear rate and the material removal rate were calculated.

It was shown that the generator programs Cu-Ti 15-15 and Cu-Ti 9-9 offer the potential for prospective machining of Ni-Ti sheets for elastocaloric applications, since they produced low roughness and crack-free surfaces due to significantly lower discharge energies compared to Cu-Ti 30-30. Thus, higher surface quality, reduced tool wear and higher precision was achieved. When focusing on elastocaloric applications, where the main goal is to achieve the lowest possible surface roughness and heat affected zones, Cu-Ti 9-9 offers the highest potential.

There is a significant need for further researches to achieve roughness values that meet the requirements of VDI 3400 on Ni-Ti and to assure the functionality of the machined parts for
elastocaloric applications. In addition, erratic structures were detected in the center of the removals, which indicate that the dielectric flushing needs to be optimized.

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