



# Manufacturing of Reference Defects for NDT Using Low-Energy EDM

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**Abstract.** For non-destructive testing (NDT) appropriate reference blocks are required in order to verify and calibrate a testing procedure. At BAM a special electric discharge machining (EDM) system has been developed which is able to manufacture artificial defects having a width down to 30  $\mu\text{m}$ .

Especially in the case of austenitic materials conventional EDM leads to a transformation of austenite to martensite. The martensite transformation causes a higher sensitivity of electromagnetic NDT methods (e. g. eddy current testing) at the artificial defects compared to natural defects of same size. The EDM system developed at BAM uses very low energy to avoid this material transformation. A side effect of the low-energy EDM is a lower surface roughness compared to conventional EDM.

The artificial defects manufactured at BAM are measured optically and delivered with a certificate.

A comparison of artificial defects shows the influence of material transformation on NDT and how differently the quality of the artificial defects can be.

## Introduction

Non-destructive testing (NDT) requires appropriate reference blocks with well-known inhomogeneities for verification and calibration of the testing procedures. In general parts with natural inhomogeneities are not available or insufficient due to unknown dimensions and material properties of the natural inhomogeneities. Therefore special reference blocks with artificial inhomogeneities of well-known dimensions and material properties are required. Natural cracks are simulated by small slots and pores by blind holes at this reference blocks.



## Reference Slots Compared to Natural Cracks

The main difference between manufactured reference slots and natural cracks is the cross-sectional shape (see Figure 1).

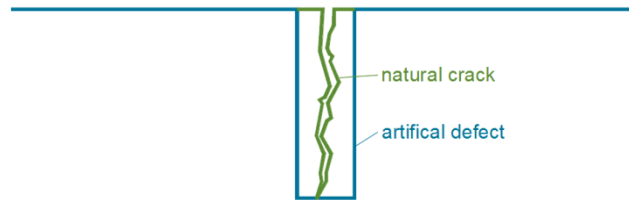


Figure 1: Cross-section of a natural crack and an artificial defect.

Another difference is the energy balance in the development of the inhomogeneity:

In the case of natural cracks there is a maximum of intrinsic energy at the tip of the crack caused by mechanical stress. This energy is minimized by growing of the crack without material loss.

Manufacturing artificial slots, external mechanical or thermal energy is applied to remove material.

These different mechanisms in the development of the inhomogeneity may result in different grain with different electromagnetic properties. Especially in the case of austenitic materials the applied energy may lead to a transformation of austenite to martensite [1].

Both the larger cross-sections of artificial slots and different grain caused by applied energy lead to a higher eddy current signal at reference slots compared to natural cracks. Using reference slots for calibration in order to size the cracks, the larger signal of the reference slots leads to an underestimation of the natural crack size. Therefore reference slots should be manufactured with low energy and as small as possible especially in terms of width.

## Low-Energy EDM

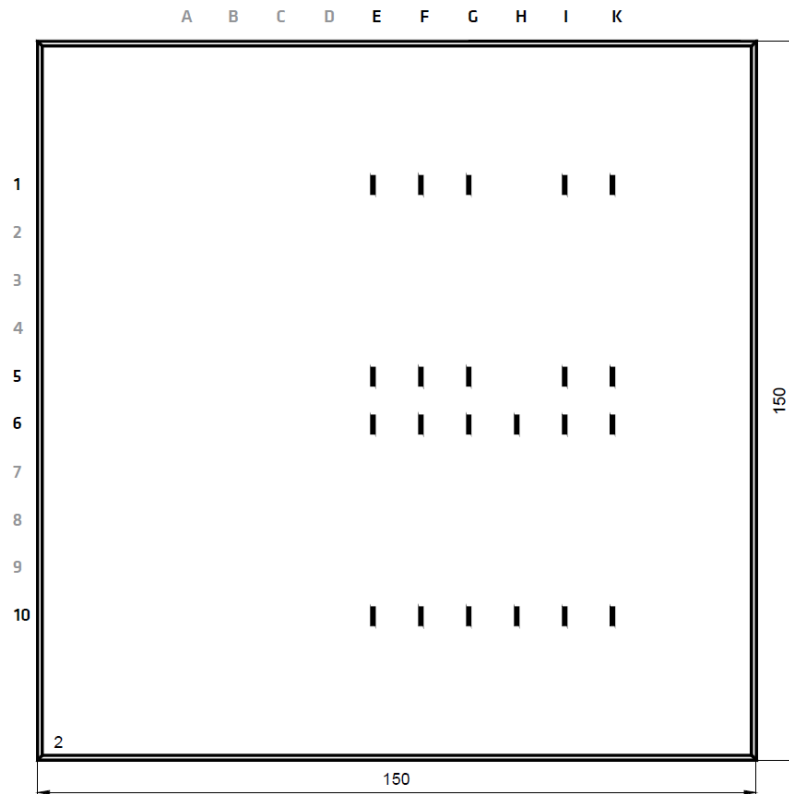
Crucial for material transformations is the surface temperature of the workpiece. Because of conventional EDM the surface is melted or even evaporated due to electric discharge sparks. While solidifying after melting, the grains of austenitic steel near the surface are transformed into two different layers: The upper layer remains austenitic enriched with carbonite from the dielectric oil and material from the electrode, the lower layer is transformed to martensite [1].

If the discharge pulse time is shorter than  $5 \mu\text{s}$  there is not enough time to heat up the surface to the melting point. Instead of melting, metal atoms are pulled out by electrostatic force without material transformation [2]. This is what we call low-energy EDM.

A special low-energy die sinking EDM has been developed at BAM 8.4 which is able to manufacture artificial defects from a width of 30 microns using low energy to minimize material transformations. The voltage can be regulated from 20 V up to 300 V. Pulse width and current of the sparks can be adjusted by choosing resistors and capacitors of a RC-circuit in a wide range. Unlike most conventional EDM, the oil which is used as dielectric media is rinsed over the workpiece and the workpiece is not immersed in an oil bath, so there are fewer limitations in geometrical dimensions of the workpiece.

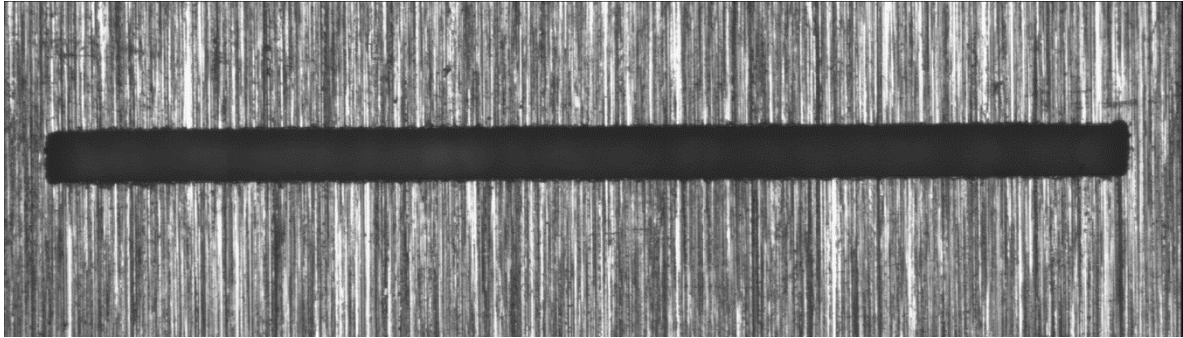
## Comparison of EDM Systems

We have manufactured multiple pairs of slots in a plate of austenitic steel 1.4301 (V2A) using the die sinking EDM developed at BAM 8.4 (Figure 2, rows 1 and 5) and a commercial die sinking EDM available at BAM 9.2 (Figure 2, rows 6 and 10). All slots have a nominal length of 3 mm and a nominal depth of 0.5 mm. Each pair of two slots was manufactured with the same parameters, one slot for NDT (Figure 2, rows 5 and 6 in the middle of the plate) and the second for destructive examinations (Figure 2, rows 1 and 10 half way to the edges).

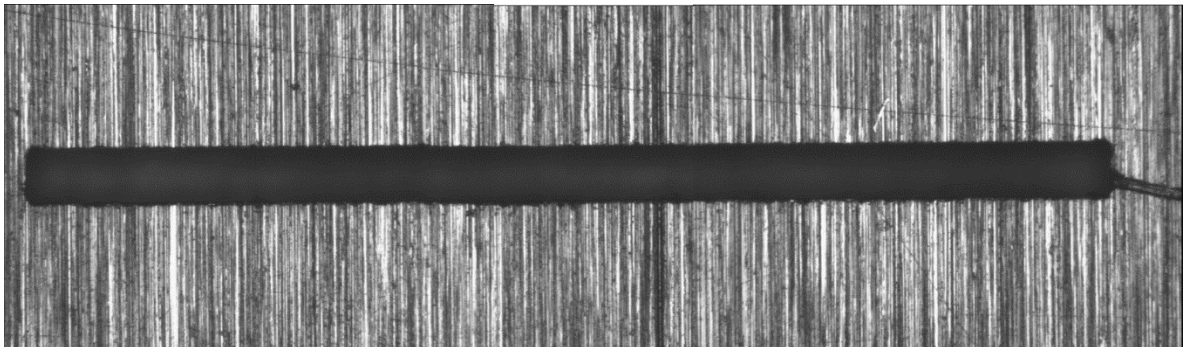


**Figure 2: Scheme of the austenitic steel plate with EDM slots.  
Rows 1 and 5: BAM EDM, rows 6 and 10: commercial EDM.**

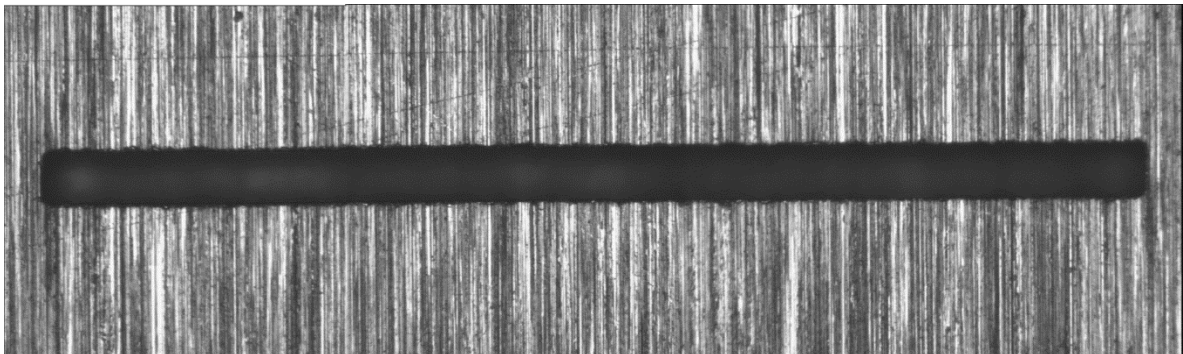
First we manufactured four pairs of slots with the commercial EDM using a wolfram electrode with a thickness of 100  $\mu\text{m}$ . Such an electrode is unusual for commercial EDM but common for BAM EDM. We used the lowest possible and the double energy with and without finishing. Because the default setup of the commercial EDM for thin copper electrodes does not work for the 100  $\mu\text{m}$  wolfram electrode, we had to perform some preliminary experiments to get the right EDM parameters. The slots we achieved have a width of 150  $\mu\text{m}$  without finishing and 160  $\mu\text{m}$  with finishing (Figure 3 to Figure 6).



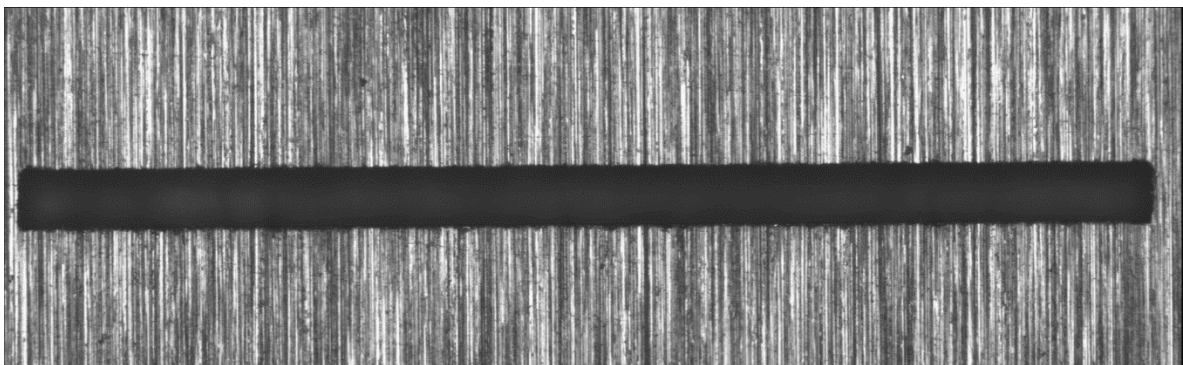
**Figure 3: Slot K6, commercial EDM, 90 V, 1.1 A, 9.2  $\mu$ s, 100  $\mu$ m wolfram electrode, without finishing,  $3.07 \times 0.150 \times 0.48 \text{ mm}^3$**



**Figure 4: Slot I6, commercial EDM, 90 V, 5.4 A, 0.8  $\mu$ s, 100  $\mu$ m wolfram electrode, with finishing,  $3.06 \times 0.158 \times 0.515 \text{ mm}^3$**



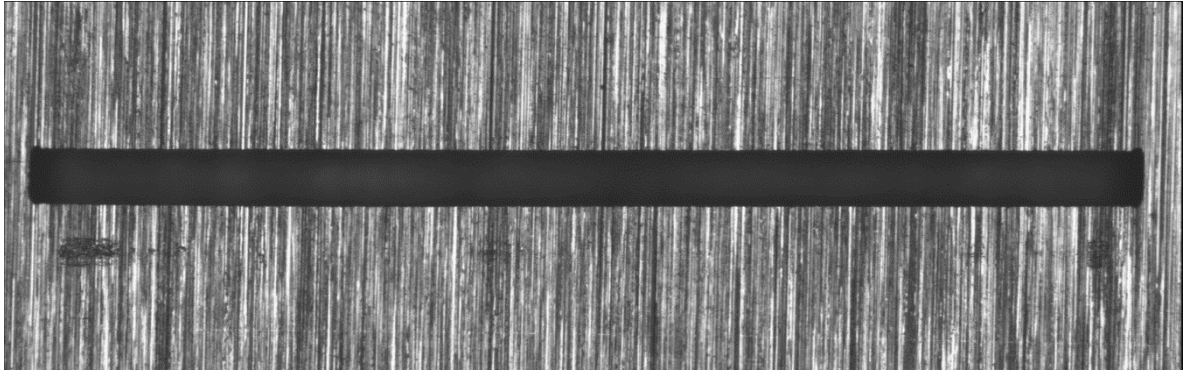
**Figure 5: Slot H6, commercial EDM, 90 V, 1.5 A, 9.2  $\mu$ s, 100  $\mu$ m wolfram electrode, without finishing,  $3.06 \times 0.155 \times 0.495 \text{ mm}^3$**



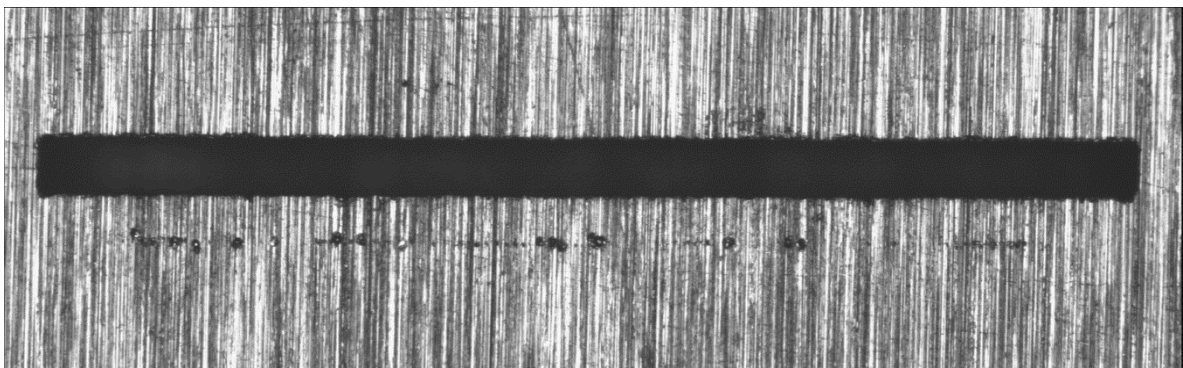
**Figure 6: Slot G6, commercial EDM, 90 V, 5.4 A, 0.8  $\mu$ s, 100  $\mu$ m wolfram electrode, with finishing,  $3.06 \times 0.161 \times 0.490 \text{ mm}^3$**

Next we used the same electrode for manufacturing two pairs of slots with BAM EDM using a very low and a relative high energy. Additional lateral movement was applied to achieve nearly the same slot width as at the slots manufactured using the commercial EDM.

These slots have a width of 145  $\mu\text{m}$  compared to 155  $\mu\text{m}$ , respectively (Figure 7 and Figure 8).

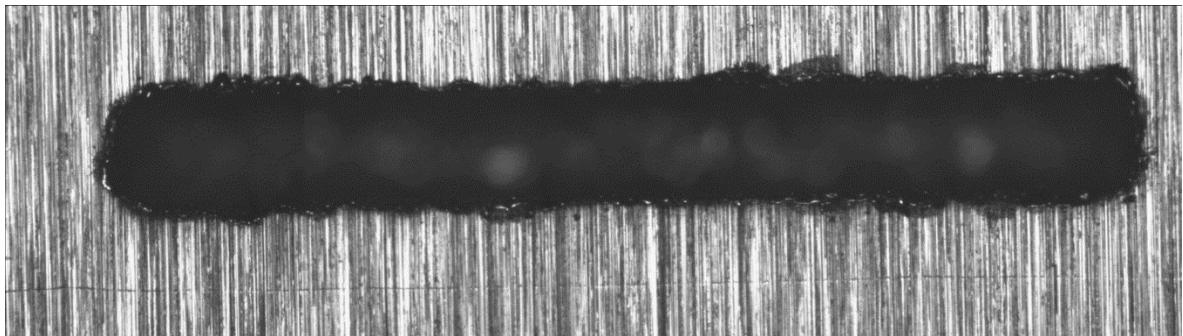


**Figure 7: Slot K5, BAM EDM, 100 V, 1.8 A, 205 ns, 100  $\mu\text{m}$  wolfram electrode, lateral movement,  $2.94 \times 0.145 \times 0.494 \text{ mm}^3$**



**Figure 8: Slot I5, BAM EDM, 200 V, 12 A, 220 ns, 100  $\mu\text{m}$  wolfram electrode, lateral movement,  $2.97 \times 0.156 \times 0.503 \text{ mm}^3$**

The next two pairs were manufactured with commercial EDM using a graphite electrode with a thickness of 220  $\mu\text{m}$  and the common parameters for this electrode. The achieved slots have a width of 370  $\mu\text{m}$  without and 460  $\mu\text{m}$  with finishing (Figure 9 and Figure 10).



**Figure 9: Slot F6, commercial EDM, 120 V, 12 A, 62  $\mu\text{s}$ , 220  $\mu\text{m}$  graphite electrode, without finishing,  $3.00 \times 0.370 \times 0.560 \text{ mm}^3$**

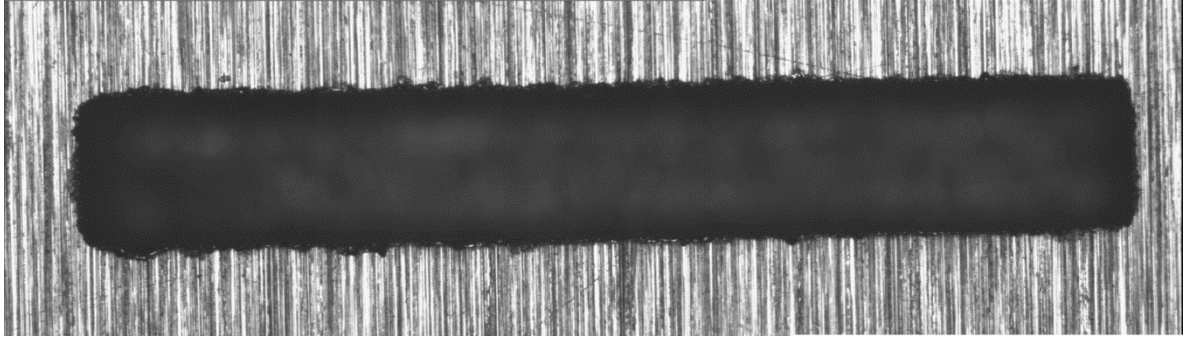


Figure 10: Slot E6, commercial EDM, 120 V, 4.2 A, 1  $\mu$ s, 220  $\mu$ m graphite electrode, with finishing,  $3.10 \times 0.460 \times 0.500 \text{ mm}^3$

Next we manufactured a slot of nearly the same width using BAM EDM. Instead of the 220  $\mu$ m graphite electrode a 100  $\mu$ m wolfram electrode with lateral movement was used to achieve nearly the same slot width (Figure 11).

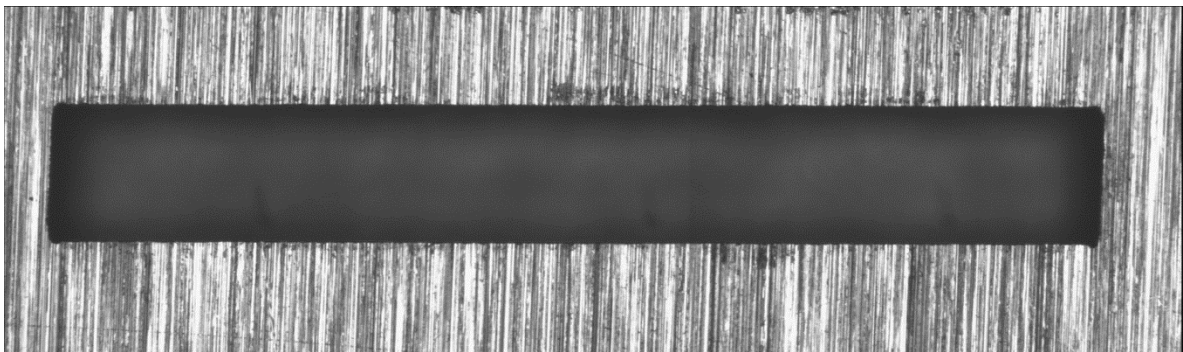


Figure 11: Slot G5, BAM EDM, 120 V, 1.5 A, 220 ns, 100  $\mu$ m wolfram electrode, lateral movement,  $2.90 \times 0.380 \times 0.580 \text{ mm}^3$

At last we tried to manufacture a pair of slots as small as possible with BAM EDM. We used a wolfram electrode with a thickness of 10  $\mu$ m at the first attempt, but reached a depth of only 0.14 mm. With an electrode of 15  $\mu$ m thickness and modified EDM parameters we succeeded in manufacturing a small slot with the desired depth and a width of 55  $\mu$ m (Figure 12).

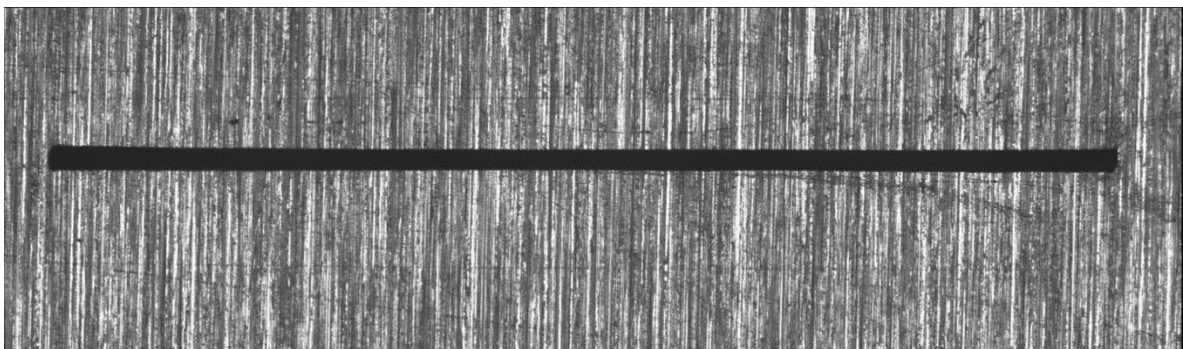


Figure 12: Slot F5, BAM EDM, 60 V, 600 mA, 125 ns, 15  $\mu$ m wolfram electrode,  $3.00 \times 0.055 \times 0.470 \text{ mm}^3$

The EDM parameters and achieved slot width are summarized at Table 1. The currents and pulse widths are measured using an oscilloscope and a current probe; the voltages are given by the spark generators.

Slots	Machine	Voltage	Current	Pulse Width	Electrode	Finishing <sup>1)</sup>	EDM Time	Slot Width
K6/10	commercial	90 V	1.1 A	9.2 $\mu$ s	100 $\mu$ m wolfram	no	4 h	150 $\mu$ m
I6/10	commercial	90 V	1.1 A	9.2 $\mu$ s	100 $\mu$ m wolfram	yes	5 h	160 $\mu$ m
			5.4 A	0.8 $\mu$ s				
H6/10	commercial	90 V	1.5 A	9.2 $\mu$ s	100 $\mu$ m wolfram	no	4 h	150 $\mu$ m
G6/10	commercial	90 V	1.5 A	9.2 $\mu$ s	100 $\mu$ m wolfram	yes	4 h 30'	160 $\mu$ m
			5.4 A	0.8 $\mu$ s				
K1/5	BAM	100 V	1.8 A	0.2 $\mu$ s	100 $\mu$ m wolfram <sup>2)</sup>	n/a	3 h	145 $\mu$ m
I1/5	BAM	200 V	12 A	0.2 $\mu$ s	100 $\mu$ m wolfram <sup>2)</sup>	n/a	30'	155 $\mu$ m
F6/10	commercial	120 V	12 A	62 $\mu$ s	220 $\mu$ m graphite	no	35'	370 $\mu$ m
E6/10	commercial	120 V	12 A	62 $\mu$ s	220 $\mu$ m graphite	yes	40'	460 $\mu$ m
			4.2 A	1 $\mu$ s				
G1/5	BAM	120 V	1.5 A	0.2 $\mu$ s	100 $\mu$ m wolfram <sup>2)</sup>	n/a	5 h 30'	380 $\mu$ m
E1/5	BAM	60 V	0.5 A	0.1 $\mu$ s	10 $\mu$ m wolfram	n/a	2 h 30'	35 $\mu$ m <sup>3)</sup>
F1/5	BAM	60 V	0.6 A	0.1 $\mu$ s	15 $\mu$ m wolfram	n/a	8 h 30'	55 $\mu$ m

Table 1: EDM parameter and achieved slot width.

<sup>1)</sup> Two-pass EDM: 1<sup>st</sup> rough machining with higher energy, 2<sup>nd</sup> finishing with lower energy and lateral movement.

<sup>2)</sup> Lateral movement to increase slot width. <sup>3)</sup> 0.14 mm depth only.

## Eddy Current Testing

We scanned the area of artificial defects with a set of different eddy current probes at different frequencies. The results are quite similar. Only the results of the differential probe DT 3702 from PLR [3] at a frequency of 500 kHz are shown here (Figure 13 to Figure 16).

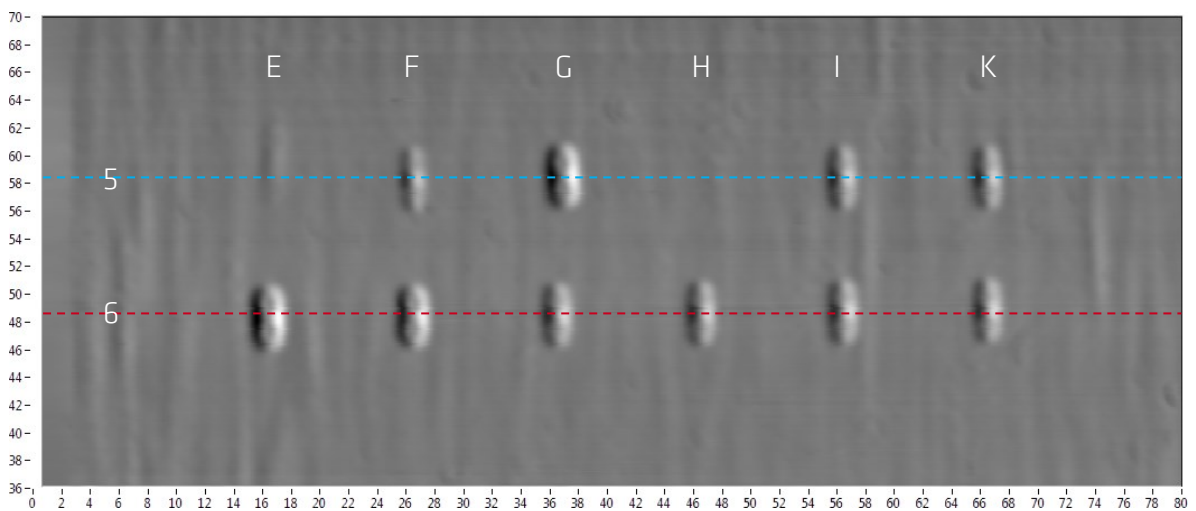


Figure 13: Eddy current image of EDM slots rows 5 (BAM EDM) and 6 (commercial EDM).

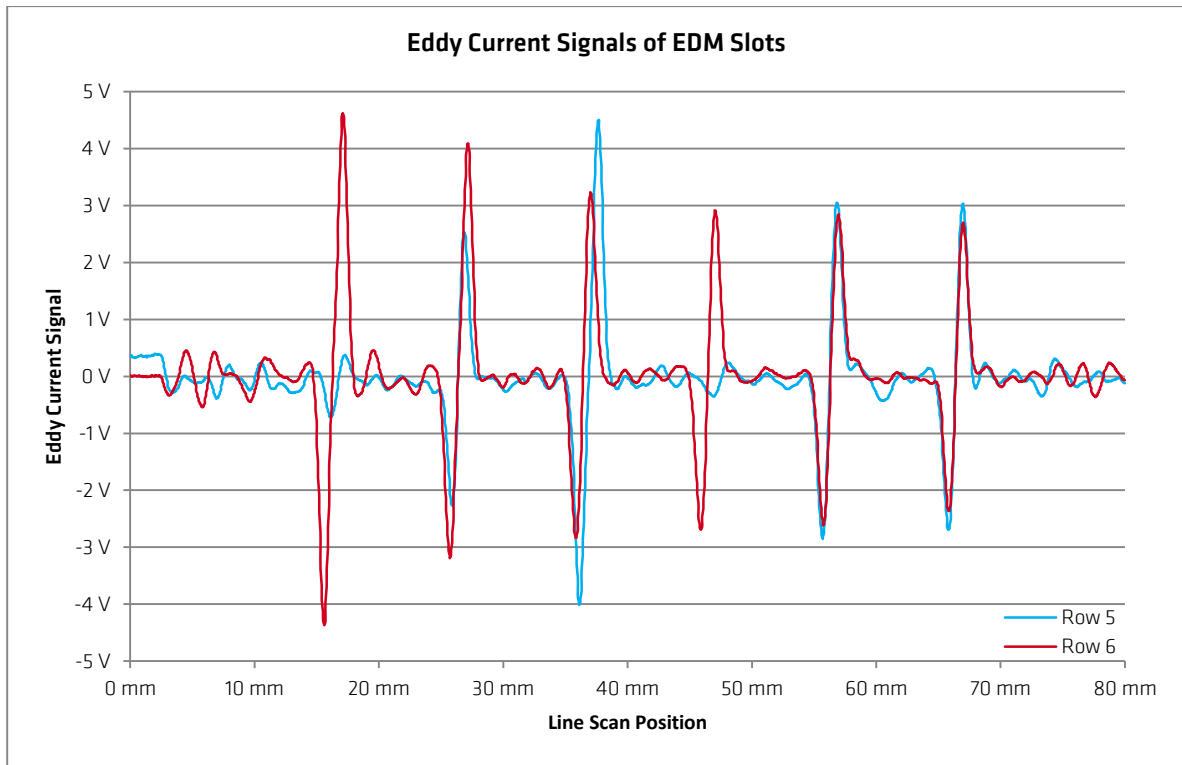


Figure 14: Eddy current signals of the center lines of rows 5 (BAM EDM) and 6 (commercial EDM) using the differential probe DT 3702 from PLR at a frequency of 500 kHz.

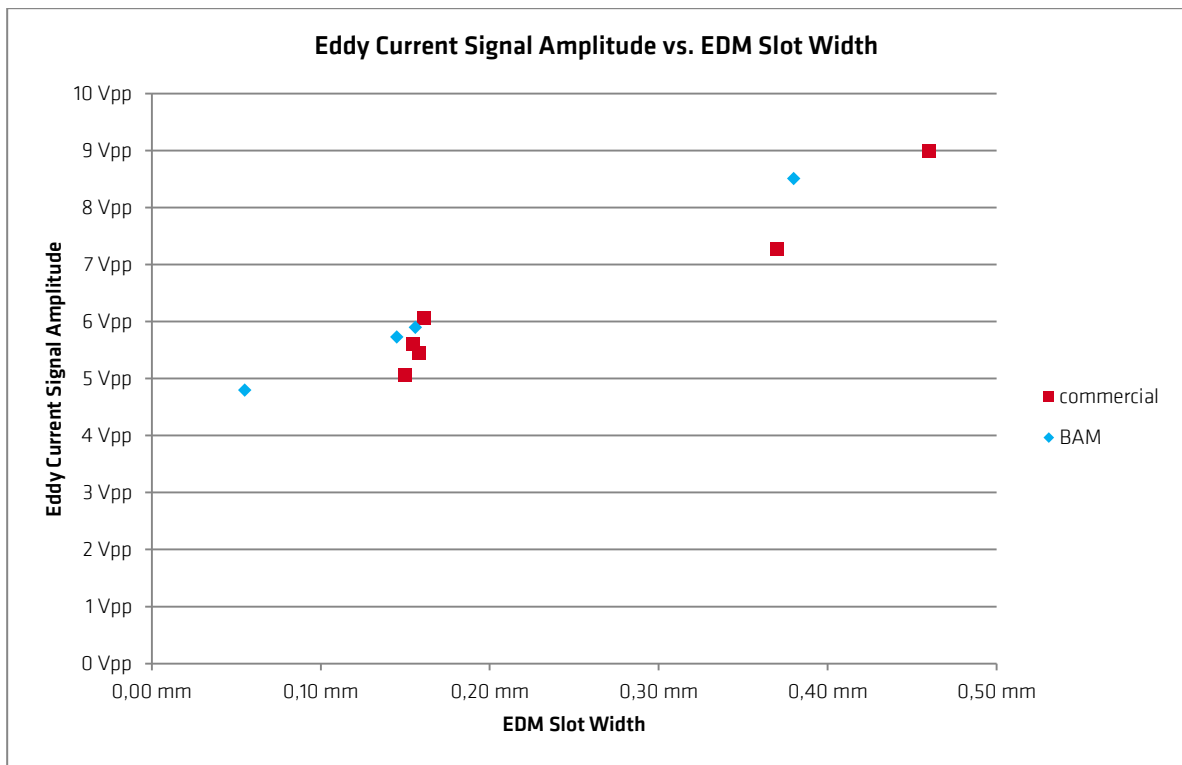


Figure 15: Peak to peak voltage of eddy current signal versus slot width.



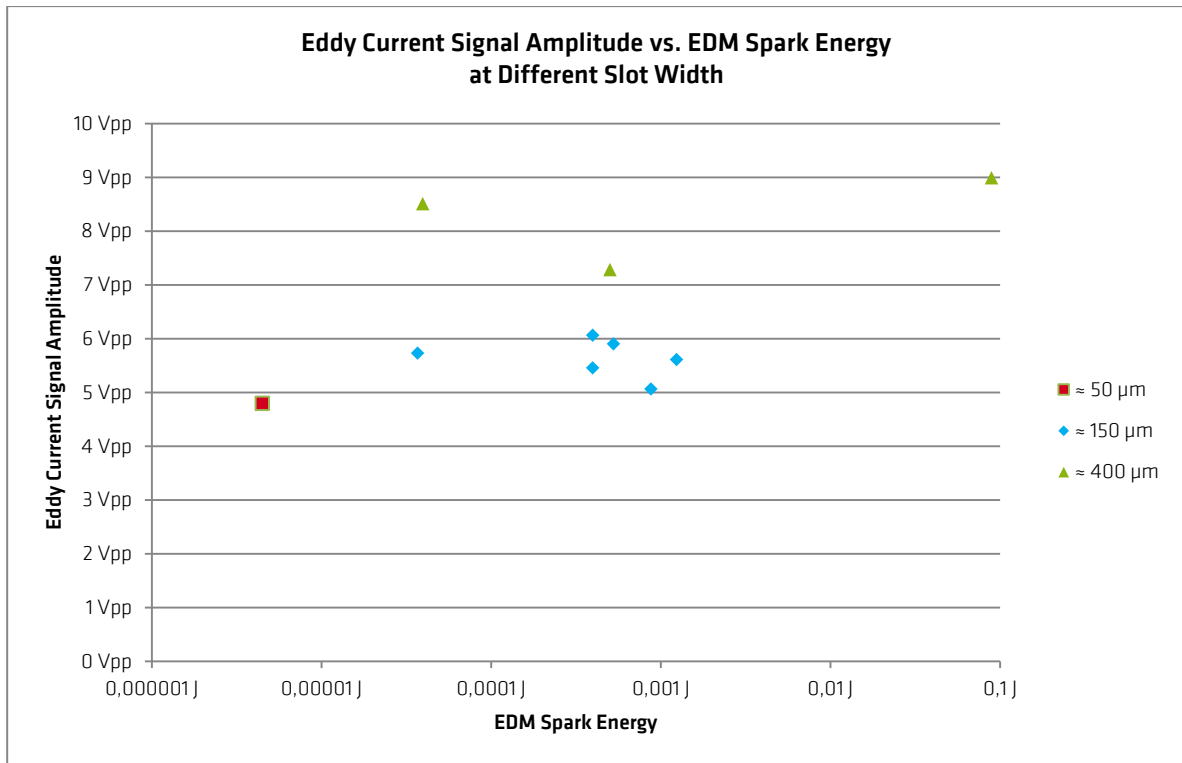


Figure 16: Peak to peak voltage of eddy current signal versus EDM spark energy at different slot width.

There is a significant relationship between the eddy current signal amplitude and slot width (Figure 15). The signal amplitude of slot E6 manufactured with the commercial die sinking EDM using a conventional 220  $\mu\text{m}$  graphite electrode is 5.5 dB greater than the signal of the 55  $\mu\text{m}$  slot manufactured with low-energy EDM from BAM using a special 15  $\mu\text{m}$  wolfram electrode. Therefore artificial slots simulating cracks should be manufactured as small as possible, because natural cracks are in general smaller than artificial slots (Figure 1).

Contrary to earlier statements, there is no relationship between eddy current signal amplitude and EDM spark energy visible (Figure 16). Especially in comparison between slot F6 and G5 we expected higher differences in eddy current signals caused by the different mechanisms of low-energy and conventional EDM [2].

One reason can be that the steel plate had some basic content of martensite before EDM so that the influence of the additional material transformation caused by EDM on the eddy current signal was very low compared to the influence of the basic martensite content.

Another reason for the unexpected results can be that the austenitic steel 1.4301 is EDM tolerant while other kinds of steel are more sensitive to grain transformations.

## Conclusions

Contrary to earlier statements, we found no difference in eddy current signals caused by material transformations between low energy EDM and commercial EDM.

The smallest slot with the desired depth of 0.5 mm which we achieved using BAM EDM was three times smaller than using the commercial EDM. The eddy current signal of this small 55  $\mu\text{m}$  slot is 2 dB less than the signal of the 150  $\mu\text{m}$  slots manufactured using conventional EDM.

There are commercial micro-EDM, which are able to manufacture similar small slots [4] [5] [6] [7], but these machines are limited in size and geometry of the workpiece.

The BAM EDM is able to manufacture slots from a width of 30 microns even at larger workpieces with complicated geometry (e. g. axle stubs).

Reference defects manufactured at BAM are measured optically based on ISO/DIS 25178–606:2013 [8] and delivered with a certificate.

## Outlook

Metallographic examinations are still missing due to lack of time. We will perform some further tests with other kinds of austenitic (and ferritic) steel.

## References

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