Investigations on Surface Integrity of Heat Treated 42CrMo4 (AISI 4140) Processed by Sinking EDM

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Abstract

Adjusting a resulting surface integrity prior to a manufacturing process is a big challenge in production engineering. One approach to solve this challenge is the methodology of process signatures. To develop a comprehensive process signature for Sinking EDM (S-EDM) it is necessary to describe the relationship between the applied material loadings and resulting modifications in the workpiece rim zone. It is generally considered that S-EDM is an electro-thermal process, which is significantly characterized by the heat flux due to the spark plasma. Accordingly, the main loadings during S-EDM are the arising temperatures and their temporal as well as spatial gradients in the workpiece. These loadings lead to varied surface integrity modifications. Thus, the task is to investigate the surface integrity alteration according to the initial material condition. Consequently, in this paper the effect of different annealing and heat treatment states of 42CrMo4 (AISI 4140) on the S-EDM process were investigated. Hence, changes of state variables depending on different machining parameters and the varying dissipated energy were considered. Therefore, the resulting microstructures were analyzed by scanning electron microscope (SEM). Additionally residual stress was determined and compared to the initial state. The identified changes of investigated state variables are the described modifications.

Keywords: Process Signature; EDM; Surface Integrity; Microstructure; Modelling; 42CrMo4 (AISI 4140)

1. Introduction

The material removal during EDM process takes place as a result of melting and vaporizing the workpiece material as well as flushing out molten metal by dielectric [1,2]. The required thermal energy is provided by local plasma discharges. But thermal energy is not only responsible for the material removal. Also other material properties are influenced by high temperatures. This influence of material properties can be described as change of state variables in consequence of an application of energy. This approach to describe manufacturing processes was made by Brinksmeier et al. [3,4]. They divided the manufacturing process in three sections: process parameters, material loadings and material modifications. The transfer function correlating the material loadings in the workpiece rim zone with the resulting material modifications is called process signature. Loadings during EDM process can be temperatures or stresses and modifications are changes in hardness or residual stress states, for example. Additionally, they distinguish between mechanical, thermal and chemical energies, whereupon the EDM process is related to processes with mainly thermal energy. The process signatures of different manufacturing processes enable adjusting a resulting surface integrity state by choosing the right manufacturing process and process parameters prior. As mentioned before in EDM process thermal energy is the reason for the resulting surface integrity and thus life cycle time of the final workpiece [5,6]. As a result of high absolute temperatures and temperature gradients rim zone state variables like residual stress, phase composition, hardness and roughness change.
To develop the EDM process signature it is necessary to examine the dissipating energies during the process because they are relevant to determine the material loadings in the workpiece rimzone. This intention is quite difficult for the EDM process cause of high temperatures and temperature gradients in very short time periods and high spatial localization [7]. However, total electric energy which dissipates during the process can be measured accurately. The ratio of energy which dissipates finally in the workpiece was investigated by Kunieda et al. [1,8]. With their assumption it is possible to simulate the temperature distribution by solving the heat conduction equation (1) [7,9]. So it is possible to correlate the measured modifications with the simulated loadings in terms of process signature.

\[ \frac{\rho \cdot c_p \cdot \partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial z^2} \]  

(1)

Furthermore, the workpiece material respectively its heat treatment states have to be considered. Consequently, for this intent heat treatment states normalized and tempered HRC 30 of 42CrMo4 (AISI 4140) were chosen and investigated in this examination.

2. Experimental set-up

For this study the steel alloy 42CrMo4 (AISI4140) in two different microstructure states, normalized ferrite-pearlite and one hardened and tempered state, were investigated. The microstructures of base materials are shown in Fig. 1.

The ferrite-pearlite microstructure (a) is characterized by its lamellar pearlite structure with embedded pure ferrite (dark areas in Fig. 1(a) grains, whereas the hardened and tempered microstructure (b) has a much finer grain structure.

The experiments were done on a GFMS AgieCharmilles FORM 2000. As tool electrode material a fine grain graphite with Agraphite = 15 mm x 15 mm cross-section area was used. The sinking depth was \( d = 1 \) mm consequently the removed volume was \( V_R = 225 \) mm\(^3\). Additional to the material microstructure, the discharge current and discharge duration were varied, Table 1.

![Fig. 1. SEM recordings of (a) ferrite-pearlite normalized; (b) hardened and tempered HRC 30.](image)

Table 1. Design of experiments for roughing

| Parameters | Values |
|------------|--------|
| Pulse current \( I_e / \) A | 9, 23, 24, 68 |
| Pulse duration \( t_e / \) µs | 50, 100, 150 |
| Material state / | normalized, hardened and tempered |

The current and voltage characteristic of each discharge were analyzed in real time with an FPGA based process monitoring tool [10]. Consequently it is possible to characterize each single discharge and evaluate afterwards. The discharge energy dissipating during one pulse can be determined by:

\[ E_e = \int_{t=0}^{t_e} U_e \cdot I_e \, dt \approx U_e \cdot I_e \cdot t_e. \]  

(2)

The EBSD measurements were performed using a JSM7000F scanning electron microscope by JEOL equipped with Schottky field-emission gun and a combined EDX/EBSD-system by EDAX-TSL consisting of a Si(Li) - EDX detector and a "Hikari" EBSD camera. For the measurements the system was operated at an electron energy of \( E = 20 \) keV and a probe current of approximately \( I_p = 20 \) nA. The measured fields have been scanned with a step size of \( x_{SD} = 50 \) nm each. The software used for measurement and data evaluation was OIM Data Collection and OIM Analysis by EDAX-TSL, both in version 6.2.

3. Results and discussion

In the following chapters aspects of surface integrity are investigated regarding different impact of heat treatment states. Additionally, fundamental facts of surface integrity were verified for the material 42CrMo4.

3.1. Material removal rate (MRR) and roughness

Fig. 2 shows the material removal rate MRR according to the average discharge energy per spark \( E_e \). Every mark represents one experiment. Generally, it can be seen that higher
discharge energy results in higher removal rates. This is a fundamental correlation which is already documented by many authors [11,12]. The reason for this is that an increase of discharge energies increases the amount of material removed during each discharge. The comparison of the two microstructure states shows no significant differences.

The roughness of EDM machined surfaces originates from the overlapping discharge craters and resolidified molten metal which is thrown out during plasma channel collapse [13]. Due to the pressure drop evaporated dielectric becomes liquid abruptly and flows into the formed cavity. Partly the solidified particles are flushed away by dielectric and partly the molten metal settles down on the workpiece surface.

In Fig. 3 the resulting roughness Ra against discharge energy for all experiments are shown. Like mentioned before, higher energy increases the amount of molten metal and thus the crater volume. Consequently, the roughness increases, too [14]. A significant difference between the two material states cannot be observed.

To identify the main effects on the surface roughness in Fig. 4 the roughness is shown against the pulse current Ie. It can be observed that with increased current the roughness is higher for a given short pulse duration. This results are in good accordance with other authors [15,16].

Furthermore, with increasing pulse duration the roughness decreases. The enlargement of plasma channel with increasing pulse time could be a reason for this phenomenon [16]. One model for this was presented by Perez [17]. He developed a time-depended empirical model of plasma channel radius:

\[ r_c = a \cdot t_e^n \]  \hspace{1cm} (3)

Hence, not only the energy is responsible for resulting surface integrity but also power and power density.

Fig. 4. Analysis of EDM parameter main effects on surface roughness.

Because the material removal rate and the roughness are big scale modifications no difference between the microstructure states can be observed. Especially, the removal rate is influenced by the thermo-physical properties of the machined material. They can differ between varying grain structures but the discharge radii occurring with the considered parameters overlap many grains and thus average the thermo-physical properties (Fig. 5).

Fig. 5. Machined surface of normalized 42CrMo4 (pulse time te = 50 µs).

3.2. Recast layer

Typical for an EDM’ed surface is the recast layer which is the result of resolidified molten metal on the surface. Thus, it is susceptible for micro cracks because the melt cools down very fast and thermal stress is produced. This cracks influence the life cycle of the resulting workpiece. Accordingly, the aim of good adjusted EDM process is to minimize the recast layer. A relationship between discharge energy and recast layer thickness is shown in Fig. 6. The thicknesses were evaluated by different SEM recordings and averaged afterwards.

Fig. 6. Influence of discharge energy on the recast layer thickness.
Despite of a small number of specimens it can generally be seen that higher discharge energy results in a thicker recast layer. This is caused by a larger amount of metal which melts and resolidifies on the surface. This was also observed by Guu et al. and Rebelo et al. [14,15].

The microstructure seems to have no serious effect on the recast layer thickness. The normalized as well as the tempered and hardened specimens were casted from the same raw material. Thus, it is clear that the both materials on the polycrystalline scale, i.e. averaged over a couple of grains have the same properties. That applies to the molten material more than ever, too. Consequently it was expected that there were no significant differences.

In Fig. 7 both rim zones are shown. The specimens were prepared with a nickel coating to protect the recast layer (at the top right). The origin material can be observed in the bottom left corner. The recast layer is the homogenous looking layer next to the nickel coating. This figure shows only a small detail view which explains the difference in thickness. In the statistical average over the whole specimen the layers have a similar thickness. In the recast layer dendritic solidification took place, Fig. 8. This kind of solidification mechanism only occurs if an undercooled melt exists [18], for example, when the cooling rate is very high like in EDM process [7].

![Fig. 7. Recast layer of normalized and hardened and tempered 42CrMo4 (AISI 4140)](image)

3.3. Heat affected zone (HAZ)

Next to the recast layer a zone can be noted which was not melted but influenced by high temperatures. Caused by high temperatures above the austenization temperature A_c the material recrystallized to a finer structure (Fig. 7).

![Fig. 8. Dendritic structure in the recast layer (I_e = 23 A, t_e = 150 µs).](image)

In Fig. 9 the thickness of this heat affected layer is plotted for different average discharge energies and microstructure states. The thicknesses were evaluated by different SEM recordings and averaged afterwards. Analog to the recast layer it can be observed that the heat affected area increases with increasing discharge energy. This effect can be explained with the temperature models which assume a homogenous heat source on the workpiece surface [19,20]. The more energy dissipates into the workpiece the deeper the temperature reaches the recrystallization level and recrystallization takes place.

The discharge energy can be split in pulse current and pulse time assuming a constant discharge voltage (2). Thus, the main effect on penetration depth can be determined. The relationship between the thickness of the heat affected zone and pulse time is plotted in Fig. 10.

![Fig. 9. Relationship between HAZ thickness and discharge energy.](image)

![Fig. 10. Influence of pulse time on HAZ thickness.](image)
structures cannot be made neither in Fig. 9 nor Fig. 10. But in detail rim zone view of normalized material (Fig. 11) it can be observed that different phases are influenced in a different way. The base material consisting of pearlite structure and pure ferrite grains is at the bottom of the picture. At the top left the recast layer is shown. Between there is a zone where the sharp structure of pearlite blurs. It blurs more and more the more the distance to the recast layer decreases. The pearlite consists of ferrite and cementite which is arranged in lamellar structures. Increasing temperature induces a diffusion of carbon from the cementite lamella into the surrounding ferrite. Consequently, the cementite lamella dissolves partially during heating. When it is cooled down again presumably a martensitic transformation takes place or a very fine perlite structure is built. The dark area left of the middle bottom is a pure ferrite grain. It can be asserted that the heat affected zone at the ferrite grain is locally narrower. The reason for this phenomenon is the less carbon content of ferrite grain. Accordingly, no martensitic or perlite transformation is possible.

This influence of single grains in hardened and tempered material cannot be observed, Fig. 12. The difference between normalized and tempered and hardened microstructure is on the one hand the grain size and on the other hand the different phases. In hardened and tempered material every grain has the same phase but in normalized there are two different phase structures, ferrite and pearlite.

The stress peak is not on the workpiece surface despite highest thermal loading because a stress reduction mechanism takes place. If the induced stresses are bigger than the tensile strength of the material micro cracks form on the surface. This phenomenon can be observed in Fig. 15. Due to the micro cracks the induced stress is reduced and the stress peak can be found under the surface in the rim zone.
The peak level seems to be influenced by discharge energy as well the pulse current. With higher pulse current the amount of energy dissipating in the workpiece increases. Consequently, the temperature and thus temperature spatial and temporal gradients increase, too, with assuming pure thermal effect. Accordingly, the peak residual stress also increases.

4. Conclusion

This study has investigated the effect of different heat treatment states on the resulting surface integrity after Sinking EDM process. Therefore, two different microstructure states of the tempering steel 42CrMo4 (AISI4140) were compared regarding material removal rate, surface roughness, recast and heat affected layer thickness. Additionally, residual stress of normalized material was investigated:

1. It is not sufficient to consider only the discharge energy to correlate surface integrity. Also the power and power density are important.
2. On the polycrystalline scale, which means averaged over several grains, no significant difference between the two heat treatment states could be observed. Neither the removal rate nor the surface roughness or recast layer thickness varied relevant.
3. However, on the grain scale there is a difference. The investigated ferrite grain was not that influenced by heat flux like the surrounding pearlite structure.
4. The determined residual stresses show good accordance with observations of other authors. Additionally, the influence of pulse current and pulse time was presented.

The done investigations are the first step to a comprehensive description of the process signature of EDM. In future work the achieved results have to be correlated with measured temperatures as state variable for heat conduction to determine the correlation between material loadings and material modifications. Finally, a comprehensive model of the determined interrelationships has to be developed to reach the goal to predict the resulting surface integrity.

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

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**Fig. 15.** Micro-crack formation on workpiece surface (top view).

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