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Process Signatures of EDM and ECM Processes – Overview from Part Functionality and Surface Modification Point of View

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Abstract

The concept of Process Signatures, which aggregates information on material modifications caused by thermal, mechanical and chemical process-induced loadings, is a promising new strategy to achieve a knowledge-based solution of the so-called inverse surface integrity problem. This paper presents an overview on the projection of the above mentioned concept on selected research activities for state-of-the-art Electrical Discharge Machining (EDM) as well as Electrochemical Machining (ECM) technologies. Within the paper representative process application examples are used to briefly discuss the process induced energy dissipation and the resulting surface modifications. Similarities and differences due to the distinct active physical principle of material removal are analyzed. Finally, a methodology to enable a standardized comparison of material loadings and resulting surface integrity in future will be introduced.

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Keywords: Surface Integrity; Process Signatures; EDM; ECM

1. Introduction to the Concept of Process Signatures

In industrial practice, the generation of a desired surface integrity of high performance components is still an iterative process based on experience. Despite the findings of researchers correlating the process parameters with the resulting surface integrity, until today, it is not possible to deduce the required process parameters from a given desired surface integrity, [1]. An example for this so-called inverse surface integrity problem is given in Fig. 1. Within a collaborative work in 2010 of the International Academy for Production Engineering CIRP a workpiece surface with defined compressive residual stresses of 200 MPa should be manufactured by experts using different machining strategies. The results show impressively that still nowadays a deterministic achievement of this goal is not possible, cf. [2].

The inverse problem shall be addressed by a new approach focusing on process-independent correlations between the thermal, mechanical and chemical loads within the workpiece material and the resulting material modifications.

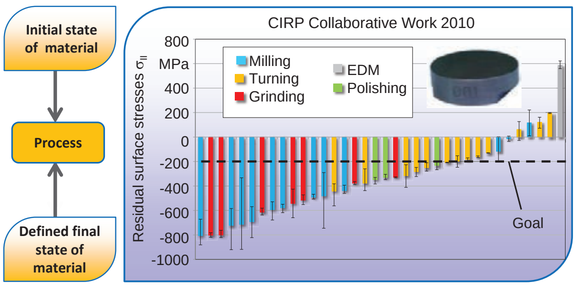

Fig. 1. Example for the inverse surface integrity problem in machining to achieve a targeted surface modification, based on [2].

The concept of Process Signatures, which aggregate information on material modifications caused by the physical conditions to which a material is subjected to on different levels of scale, is therefore a promising strategy to achieve a knowledge-based solution of the inverse surface integrity problem, [1]. While process modelling and simulation

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approaches are still very limited, cf. [3], this paper presents an overview on the projection of the above mentioned concept on selected research activities for state-of-the-art Electrical Discharge Machining (EDM) as well as Electrochemical Machining (ECM) technologies from an application point of view. Within the paper representative process examples are used to briefly discuss the process induced energy dissipation and the resulting surface modifications for dedicated areas of use. Finally, a methodology to enable a standardized comparison of material loadings and resulting surface integrity for both EDM and ECM processes will be introduced.

2. Examples of EDM- and ECM-based Process Signatures

EDM and ECM processes as advanced manufacturing technologies with unique capabilities due to their non-mechanical material removal principles can be found in different areas of application in industry offering a better alternative or sometimes the only alternative in generating accurate 3-D complex shaped macro, micro and nano features and components of difficult-to-machine materials, [4]. Typical as well as innovative examples of application for the most important areas of application – die and mold manufacturing, turbomachinery component manufacture, tooling and prototyping and medical engineering – are shown in Fig. 2. In addition also combined and even hybrid EDM and ECM processes are known with superior overall process performance, see [5].

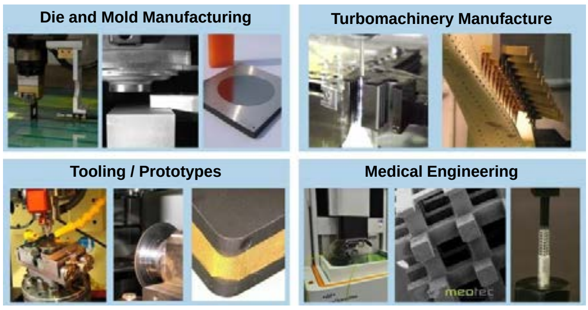

Fig. 2. Industrial areas of application of EDM and ECM defining specific requirements from part functionality and surface modification point of view.

In all areas of application the final surface integrity defines the later part performance. Therefore, the machining processes have to be designed and executed in such a way that the specific operation demands are fully met by the remaining surface modifications of the machined part. From application point of view different manufacturing processes could only compete with each other when providing at least the same part functionality and therefore similar material modifications.

The following section will give a brief overview on contemporary research activities of EDM- and ECM-dependent surface modifications and the resulting part performance and functionality for typical industrial applications with their specific needs. While EDM incorporates thermal energy dissipation, ECM purely relies on a chemical material removal principle.

The first example shown in Fig. 3 focusses on the bending fracture strength of cemented carbides as a function of the applied Wire-EDM strategy and therefore the thermal material loading. Test cuts were performed on different machine tools (Cut2000 with latest generator technology and AC270 with 20 years old technology) and for different dielectric fluids (water-based and CH-based). It can be seen that the fracture strength for the EDM experiments is correlating with the induced surface residual stresses and is somewhat independent from the surface roughness Ra. An explanation for good surface roughness but high residual surface stresses is given on the right side of the figure. Usually thermal damage of all former (trim) cuts should be removed with the following cuts but when high-energetic early cuts result in a deep thermal damage a solely surface smoothing for good surface finish is not capable to remove this layer. Therefore, these aspects of surface modification have to be taken into account when EDM strategies are defined.

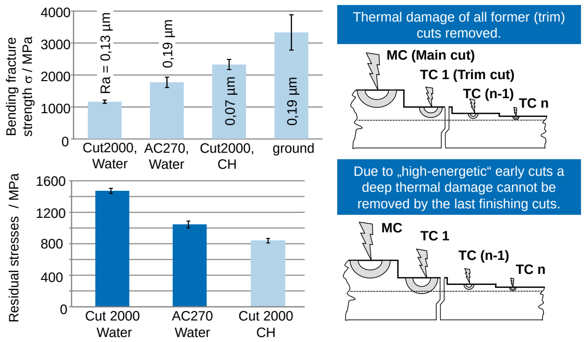

Fig. 3. Bending fracture strength of cemented carbides (representing the machining of dies) as a function of the applied Wire-EDM strategy, [6].

The second example deals with research on Wire-EDM as a technological alternative to broaching for the manufacture of fir tree profiles for turbomachinery component manufacture cf. [7]. Due to the thermal material removal principle Wire-EDM allows the robust manufacture of precise geometries for advanced difficult-to-cut materials, see Fig. 4.

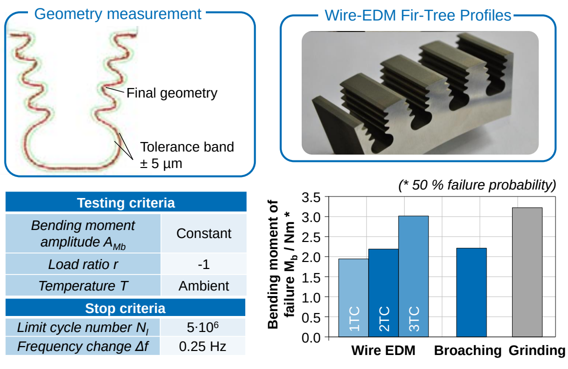

Fig. 4. Bending fatigue strength of Inconel718 (representing the machining of fir tree slots in rotor disks) as a function of the applied EDM strategy, [8].

The EDM-based heat dissipation and the resulting surface modification (thermally influenced rim zone) requests a comprehensive technology comparison for resulting part functionality as the conventional broaching results in a different thermo-mechanical rim zone modification, see [8]. Just from pure metallurgical studies of cross sections it is not possible to judge on the comparability of these rim zones. Therefore, bending fatigue strength tests have been performed for broached as well as EDMed specimens. It can be concluded that depending on the Wire-EDM strategy – i.e. number of trim cuts (TC) – a similar or even superior level of enduring bending moment (failure probability curve for 50%) compared to broaching could be achieved. Therefore, somehow comparable characteristics of the final surface modification as the result of the two process signatures can be deduced.

The third example shows the increase of lifetime of gears by a factor of 3 for the flank load carrying capacity comparing contemporary Wire-EDM technology with the industrial standard grinding process. By applying appropriate finishing trim cuts a superior tribological surface modification can be achieved as combination of adequate surface roughness allowing a good lubrication and reduced heat affected zone avoiding a complete surface spelling during operation. Comparing the EDMed tooth surface before and after operation it can be seen that a distinct running-in characteristic applies incorporating a surface flattening in combination with remaining cavities as lubricant pockets. Thus, also here an advantageous process signature of the EDM technology can be assigned in comparison to the established grinding operation.

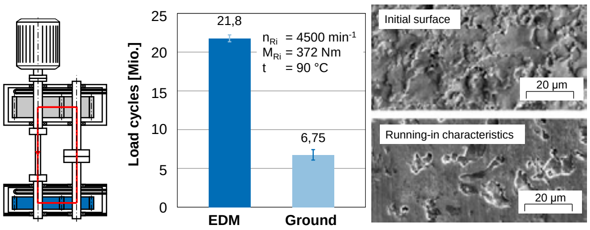

Fig. 5. Lifetime of gears as a function of the applied EDM strategy to improve the tribological characteristics for reduction of tooth flank wear.

Example four shows the thermal process signature of the EDM process on the grinding wheel surface after Wire-EDM trueing and dressing of metal bonded fine grained diamond tools, see Fig. 6. It can be seen that depending on the thermal surface load and besides of the bond removal for achieving a good grit protrusion a thermal damage of the small diamond grits takes place. Based on a defined reduced energy input due to the application of reduced discharge energies in combination with superior cooling and flushing conditions, the amount of graphitization can be minimized. For the given example of a diamond grit with a diameter of d = 10 µm the thermal damage can be kept limited to a depth of just s = 0.5 µm. The according analysis was executed applying EELS (Electron Energy Loss Spectroscopy) analysis of the carbon modifications on a lamella of the diamond grit, see [9].

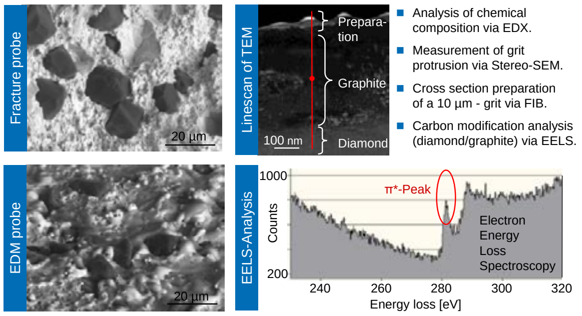

Fig. 6. Surface integrity of metal bonded diamond grinding wheels as a function of Wire-EDM trueing and dressing strategies, [9].

The next example focusses on the influence of EDM and ECM process signatures on resulting biocompatibility of medical implants, see Fig. 7. The concept of a surface enlargement by macro and micro structuring with EDM technologies in combination with a surface alteration by an ECM-based Plasma Electrolytic Oxidation (PEO), cf. [10,11], allows the defined control of the degradation behavior of biodegradable magnesium implants. Besides the degradation behavior also the resulting biocompatibility plays an important role for the later part functionality. While the EDM surface features low cell viability (most likely due to toxic copper particles from the wire electrode settled on the surface) compared to the ground reference probe, the PEO surface reveals superior cell viability as a result of the surface oxidation.

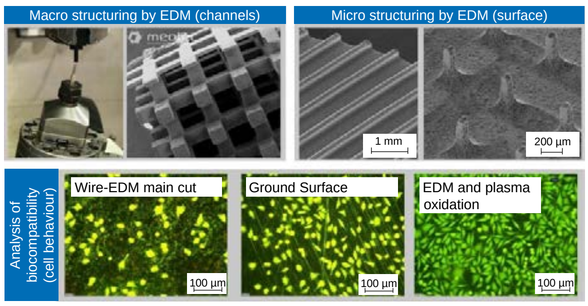

Fig. 7. Biocompatibility of implant surfaces as a function of the applied machining strategy (EDM and PEO – Plasma Electrolytic Oxidation), [6].

A last example for EDM-based surface modifications due to thermal energy dissipation is shown in Fig. 8. In an experimental study the influence of different Wire-EDM roughing and finishing steps have been evaluated for the machining of precise and filigree flexure hinges geometries with high aspect ratios, cf. [12]. Applying 9 trim cuts with reduced discharge energy levels in a CH-based dielectric a final surface roughness of Ra = 0.086 µm could be achieved for the given steel workpiece. The thickness of the white layer generally amounts to less than t = 1 µm according to the given cross section views. Depending on a given filigree geometry (e.g. a small base of b = 40 µm or a sharp edge) the process inherent heat dissipation into the material could be interfered resulting in an unwanted heat accumulation around the current discharge position. As a result an increased heat affected zone could come into existence. Such an effect was detected by EBSD-analysis (Electron Backscatter Diffraction) for a wedge-shaped test geometry. This analysis shows the local alteration of crystal orientation due to a process-dependent material loading. It can be seen that for comparable large geometries an alteration layer in the order of magnitude of the known heat affected zone is visible but for the tip of the specimen this zone is extensively widened until finally the whole workpiece material gets affected and altered.

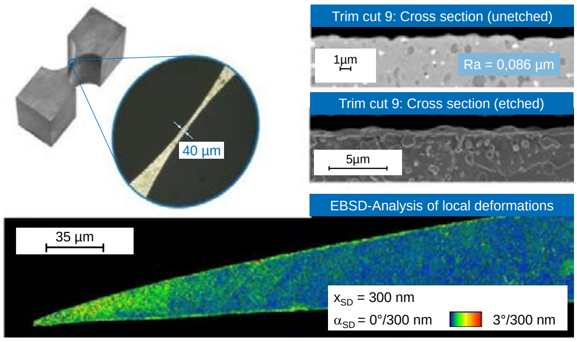

Fig. 8. Thickness of thermally altered layer as a function of EDM technology and given geometry for the machining of precise filigree flexure hinges, [12].

The final example shows the process signatures of ECM in terms of resulting material modifications. As the energy dissipation is only chemical-based no thermal or mechanical rim zone influence (i.e. white layer, deformed grains, etc.) is visible in according cross sections, see [13] and Fig. 9. But depending on the machining conditions (electrical parameters, electrolyte system, etc.) a locally non-uniform dissolution of different workpiece material (micro) phases could take place resulting in a process-induced roughness or waviness. In this context local pitting corrosion or the formation of oxide layers must also be recognized as process dependent material modifications.

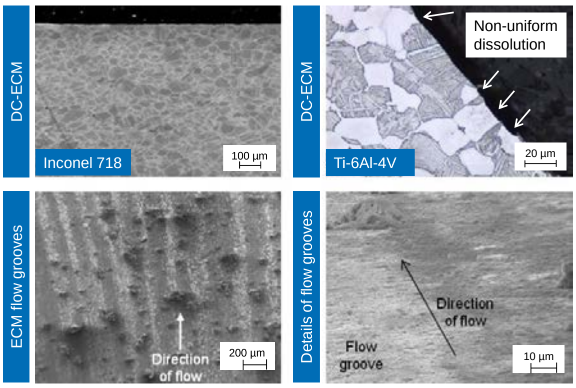

Fig. 9. Workpiece surface modifications (local dissolution and flow grooves) resulting from direct current DC-ECM processes, based on [7, 14].

In addition flow grooves are undesirable effects occurring during bad or inhomogeneous electrolyte flushing conditions. These grooves, developing in regions of high flow velocities, have the appearance of stream lines. The according SEM pictures show that the surface within the valleys is very irregular and not smooth (left figure). However, there are lot particles on the surface, but no systematic triggering of flow grooves is recognizable. This is also in account with the fact that these grooves occur localized and not probabilistic distributed. In addition, the differences in height between surfaces and valleys are very small (right figure), [14].

Similar effects of locally non-uniform workpiece material dissolution as a function of the electrolysis conditions can also be found for pulsed ECM processes (PECM), see Fig. 10. Generally better surface roughness can be achieved with higher voltages and therefore higher current densities. Depending on the applied average feed velocity different working gap sizes appear resulting in changed flushing conditions. In the given example, the surface roughness can therefore be minimized by optimizing the process via the given parameters.

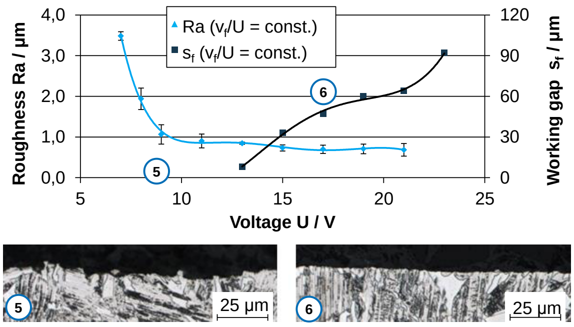

Fig. 10. Workpiece surface integrity (roughness, local dissolution) of gamma titanium (TiAl) as a function of the applied PECM machining strategy [15].

To which extent these ECM-based effects of locally non-uniform dissolution, corrosion and oxidation as well as flow grooves negatively influence the later part functionality has to be analyzed in detail for the specific application areas.

3. Methodology for a Standardized Process Comparison

The suggestion to develop process signatures is based on the fundamental assumption that all manufacturing processes are energy driven. Energy conversion and energy dissipation will impact finger prints in the material and will thus determine the final surface and subsurface properties. From this observation it can be concluded that materials “don’t know processes”. They do solely react to the physical and chemical impacts resulting from the above mentioned energy flow. This view is schematically illustrated in Fig. 11 which compares a cutting process with a laser etching process. From an engineering point of view these processes are totally different. However, from a workpiece material’s point of view the physical and chemical actions along a causal sequence are basically very much comparable, [16].

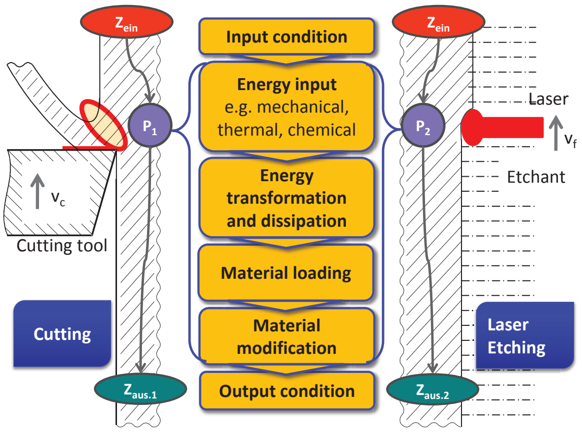

Fig. 11. Causal sequence comprised of the energy conversion, dissipation and material modification as a result of different machining processes, [16].

A practical example for the above mentioned model for further discussion is shown in Fig. 12. A comparison of grinding and Wire-EDM concerning fatigue strength and surface integrity of machined Ti6Al4V components was executed in a fundamental study. Possible areas of later application could be found in turbomachinery component manufacture as well as medical engineering as this material is applied in both areas.

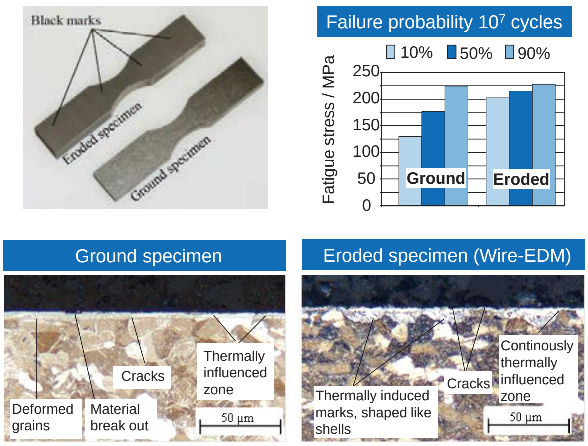

Fig. 12. Example for the comparison of two different processes from material modification and final part functionality point of view, based on [17].

A visual inspection on the resulting surface modifications was carried out in the first place. It is obvious, that the ground surface is shinier than the eroded surface. The ground series features lengthwise to the machining direction a lower roughness (Ra = 0.18 µm) than the eroded ones (Ra = 0.26 µm). Furthermore, cross section views of representative specimen from both series have been prepared. A significant thermally influenced rim zone can be seen on the ground sample. The thickness of this zone can be high as 8 µm. Furthermore grain deformation, sharp cracks and craters have been detected. All these aspects affect the fatigue life significantly. The eroded specimens have a thermal influenced zone, too. In the view which was taken lengthwise to the machining direction, there are big thermally influenced zones. The occurring marks are shaped like shells. They reach up to 20 µm into the bulk material. It can be assumed that at these positions due to unstable process conditions, more heat has been conducted into the sample. Between the shells there is a continuous layer with an average thickness of 5 µm, [17]. Concluding the gathered information on the material modification it can be stated that it is hardly possible to distinguish between the two applied process technologies when for example just the cross sections views and the surface roughness values are taken into account. Only due to the visible inspection the expert could distinguish between grinding and Wire-EDM.

Finally, from part functionality point of view both processes reach the same level of sustainable fatigue stresses. Therefore, at least for mechanical loadings during application phase, there is no difference in performance between both processes and thus each one can be recognized as an alternative for the other one. But for other performance criteria like corrosion resistance or biocompatibility there could be significant differences between the applied processes.

In order to comprehensively describe all aspects of process induced material loadings and resulting surface modifications a generic methodology for a standardized process comparison has been developed. This methodology first includes the deduction of the material loadings based on the specific process variables. In a second step the material modifications will be described as inherent consequences of the given loadings. These modifications could for example be changes in the chemical composition of the rim zone, changes of micro hardness or changes of residual stress states. The correlation between material loadings and modifications is defined as the "Process Signature". The according deduced methodologies for EDM and ECM processes are shown in Fig. 13 and 14.

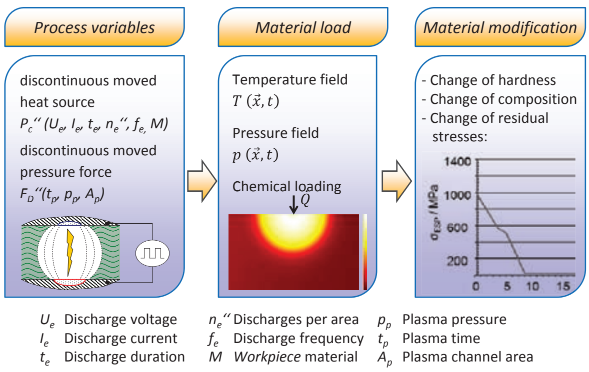

Fig. 13. Deduced methodology to generically describe EDM process signatures based on material loadings and resulting modifications, [18].

For EDM processes the discharge conditions and process mechanism have to be described as a discontinuous moved heat and pressure source resulting in material loadings based on a temperature and pressure field on the workpiece surface.

In addition also a chemical loading could take place (e.g. electrolysis effects in de-ionized water dielectrics). The resulting modifications have to be determined experimentally as well as simulation based, describing exemplarily changes in hardness, material composition or remaining residual stresses, cf. [19].

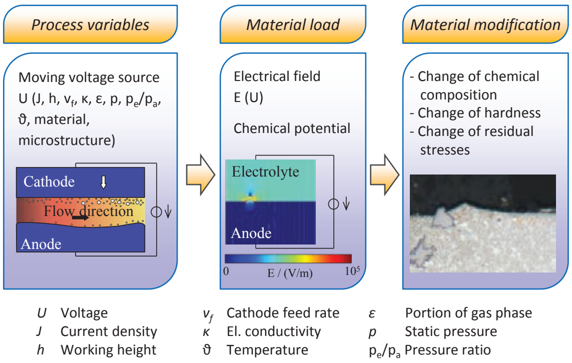

Fig. 14. Deduced methodology to generically describe ECM process signatures based on material loadings and resulting modifications, [18].

For ECM processes the local electrolysis conditions and the overall process mechanism have to be described as a moving voltage source on the workpiece surface resulting in an electrical field and a chemical potential as according material loadings. The resulting modifications especially regarding surface topography and composition have similarly to be analyzed by experiments as well as process modelling approaches. First work on this can be found in [13].

4. Summary and Outlook

The paper gave an overview on process signatures of EDM and ECM Processes from part functionality and surface modification point of view. Representative process application examples were used to briefly discuss the process induced energy dissipation and the resulting surface modifications. Similarities and differences due to the distinct active physical principle of thermal material removal by EDM and electrolysis by ECM have been analyzed in comparison to alternative manufacturing technologies. Finally, a generic methodology to enable a standardized comparison of material loadings and resulting surface integrity based on the specific process parameters has been introduced for EDM and ECM.

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