Towards zero-defect manufacturing with a combined online - offline fuzzy-nets approach in wire electrical discharge machining

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Abstract: Current practice of wire electrical discharge machining (W-EDM) is not defect free and still a number of parts produced by WEDM processes are rejected due to different defects. The main defects related to surface quality of W-EDMed parts include occurrence of surface lines, surface roughness, and recast layer (also called white layer). In this paper we characterize the different types of defects and for each of them we propose the appropriate approach to handle it. To achieve zero-defect manufacturing in W-EDM, one can intervene before starting machining operations through selecting the best combination of values of process parameters to meet required levels of performance for part quality characteristics, and during machining operations through monitoring machining conditions to predict any potential defect and take appropriate actions to prevent the effective occurrence of defects if and when predicted. This paper addresses both issues and a combined online - offline fuzzy-nets approach is proposed. It is noteworthy, that for the first time in the published literature, an approach is presented to prevent the occurrence of surface lines in W-EDM; this is accomplished by our experimentally validated system by: (i) high frequency sensing and processing of the current signal in the discharge zone; (ii) the development of a new algorithm for the detection and calculation of the duration of a series of consecutive short circuits; and (iii) the proactive adjustment of the pulse–off time through an adaptive fuzzy nets system.

Key-Words: Critical process variable; part quality characteristic; vital process parameter; WEDM

1 Introduction

In the past decades, wire electric discharge machining (W-EDM) has undergone a number of technological developments aimed at improving its process performance. Still the current practice of W-EDM is not defect-free and results in a number of surface related defects on the machined parts. The main defects related to surface quality of parts produced by the W-EDM process include the occurrence of surface lines, surface roughness and the occurrence of recast layer on the machined surface.

The scrap and rework of machined parts are identified as two dominant sources of increased cost in manufacturing industries [1]. Achieving near zero defect manufacturing will significantly reduce production cost through reducing/eliminating the costs related to post process control, and scrap and rework of machined parts with defects.

Process improvements depend not only on the development of innovative approaches to surmount the defect causing phenomena but are also contingent upon advancements in the contemporary scientific disciplines such as sensors technology, control hardware and computational capability of relevant software. Furthermore, advanced manufacturing control systems are expected to provide efficient and reliable capability to not only detect in real time the occurrence of defects in the manufacturing process but also to self-optimize in real time to minimize the production of defective parts.

To achieve near zero defect manufacturing in W-EDM, one can intervene in two ways: (i) before starting machining operations through selecting the best combination of values of process parameters to meet required levels of performance for part quality characteristics, and (ii) during machining operations through monitoring machining conditions to predict any potential defect and take appropriate actions to prevent the effective occurrence of predicted defects.

2 WEDM Parameters

WEDM is a complex machining system that is difficult to fully understand due its stochastic and nonlinear nature of the process and the multiple parameters it involves [2]. In highly complex modern EDM systems, there are up to 25 individual parameters (electrical/mechanical, etc.) influencing cutting performance [3].

The main input and output parameters for part quality prediction are defined in Table 1 in the Appendix.

In our case, the CPVs are features of the current signal in the discharge zone.

The CPVs may be influenced by VPPs and “non-adjustable” (during the machining operations) parameters but also by other unknown/unmodeled factors from the process environment.

The paper focuses on the surfacing stage of W-EDM which is a high frequency process making the tasks of data acquisition and processing, defect prediction and process parameters adjustment very challenging for online monitoring and control of surfacing in W-EDM.

In this paper we describe and characterize different surface defects of parts machined by W-EDM process and propose a combined online - offline fuzzy-nets approach to deal with these surface defects.

The paper is organized as follows. The input and output parameters involved in part quality prediction in W-EDM are considered in Section 2. Section 3 is devoted to the description and characterization of the main surface defects of parts machined by W-EDM process. The offline fuzzy-nets prediction approach, the online detection and prevention approach, and the combined approach are described in Section 4. Some concluding remarks are provided in Section 5.

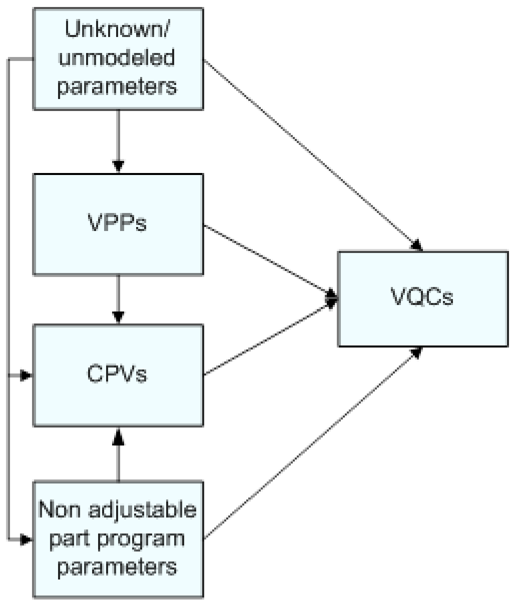

Fig. 1: Links between the types of parameters involved in part quality prediction.

The consideration of CPVs among the input parameters may allow capturing in the fuzzy rules the influence exerted by the unknown/unmodeled factors on the VQC.

The links between the different types of parameters involved in part quality prediction are show in Fig. 1.

The parameters in Fig. 1 are considered as follows:

- The unknown/unmodeled parameters are not explicitly considered
- The non-adjustable parameters are fixed a priori (before the start of machining operations)
- CPVs and VQC are variable during the machining operations and the adjustable VPPs can be varied during the machining process

The identification of all process parameters which have a significant impact on part quality characteristic is a prerequisite for the success of the application of the fuzzy-nets approach since it is based on a set of fuzzy rules generated from experimental data which establish the relationship between the process parameters and the part quality characteristic.

3 Main Surface Defects in WEDM

3.1 Description of surface defects in WEDM

Current practice of W-EDM is not defect free and still a number of parts produced by W-EDM processes are rejected due to different surface quality defects.

W-EDM involves a number of surface defects depending on the process method and machine tool system. However, this paper will address three main surface defects namely: occurrence of surface lines, surface roughness, and recast layer (also called white layer).

3.1.1 Occurrence of surface lines

The term ‘surface lines’ (Fig. 2) are used to indicate a class of machining errors generated during the W-EDM process.

Such surface defects appear like lines parallel to the wire spooling direction and can consist of simple local “darkening” of the surface or include a local variation of the surface profile with respect to the nominal surface that should have been generated by the machining process. In the first case there is no geometrical surface imperfection, but the change of colour still represents a defect for a number of applications such as the aerospace industry, as it indicates a perturbation of the process, possibly inducing a detrimental stress state or micro-structural change. Surface lines need to be prevented from occurring on the machined parts.

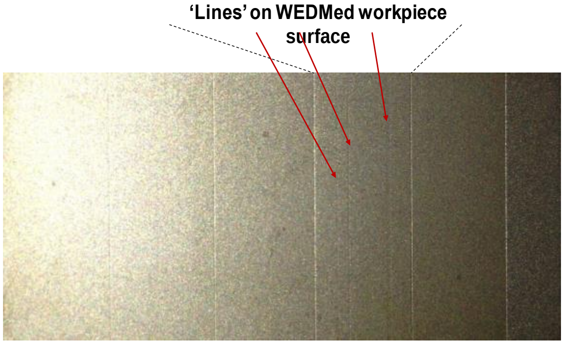

Fig. 2. Surface lines on W-EDMed part.

The literature review about W-EDM reveals the absence of any significant work dealing with the occurrence of surface lines on W-EDMed parts.

3.1.2 Recast layer

W-EDM is a thermo-electric process which removes the material by melting/evaporating it by high energy electrical sparks. In general, the thermal processes tend to modify the material properties of the machined surface. W-EDM causes damage on the machined surface due to the heat generated in the process. The damage occurs typically in the form of a recast layer (due to re-solidification of the molten metal) (Fig. 3). The recast layer must be avoided or at least its thickness must be minimized since in general, it increases the surface roughness and decreases the fatigue strength of the part as well as the corrosion and wear resistance [4].

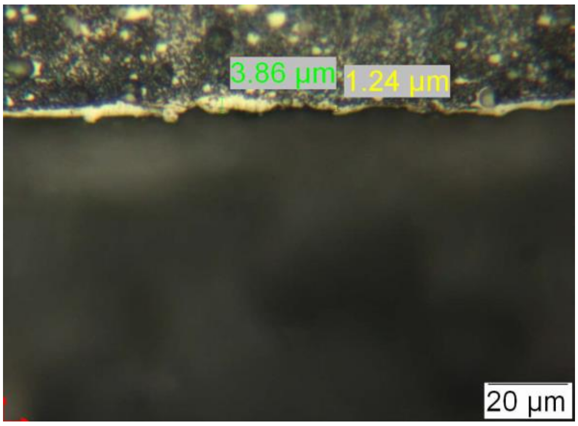

Fig. 3. Formation of recast layer during surfacing in W-EDM

The recast layer consists of molten metal particles re-deposited on the workpiece surface. Apart from causing the aesthetic devaluation of the part, the recast layer often contains micro-cracks due to thermal stress gradients. Such micro-cracks decrease the fatigue life of the components and may cause catastrophic failure of the components. Given the scale of the disaster due to a possible failure of a critical aerospace component, the aerospace industry has imposed stringent quality standards and specifications for the manufacture of critical parts. Further, in case of critical parts manufactured by W-EDM, often secondary finishing processes such as grinding, milling and chemical etching are required to remove the recast layer. Such finishing processes increase the lead time and production cost. In some cases, W-EDM process is not even recommended for the manufacture of certain aerospace parts. Additionally, a lot of effort is required to conduct surface integrity analysis of W-EDMed parts to determine the thickness of the recast layer for quality control purposes. Practically, it is not possible to apply such analysis on every machined part. Furthermore, most of the recast layer thickness techniques are destructive in nature and hence cannot be afforded to be performed on even fewer parts per batch due to scrapping of precious components.

There are two measures of recast layer thickness which can be considered: average recast layer thickness and max recast layer thickness.

3.1.3 Surface roughness

Surface roughness can be characterized considering different measures but in this paper we consider the most common one which is R_a called the arithmetic average of absolute values.

The surface roughness of a machined part is a measure of the texture of the surface of that part (Fig. 4). It is quantified by considering the vertical deviations of the surface of the part from its ideal form. The more the deviations are large, the more the surface is rough.

Surface roughness needs to be minimized. A desired level of surface roughness to be achieved is often specified by the user.

Fig. 4. Surface roughness in WEDM.

3.2 Characterization of surface defects in WEDM

The different surface defects: surface roughness, average recast layer thickness, max recast layer thickness and surface lines are characterized according to whether they represent local or global phenomena as shown in Table 2 in the Appendix.

4 Proposed Approaches

For each type of surface defect a suitable approach is indicated as shown in the following subsections.

4.1 Offline fuzzy-nets prediction approach

For global surface defects such as surface roughness and average recast layer thickness, a fuzzy logic based approach called fuzzy-nets approach [5-6] shown in Fig. 5 iis a suitable solution.

The fuzzy-nets approach is a rule-based approach. Hence, the main requirement for the application of the fuzzy-nets approach for part quality prediction is the existence of a set of input parameters which have a significant effect on the part quality characteristic that can be captured by a collection of fuzzy rules.

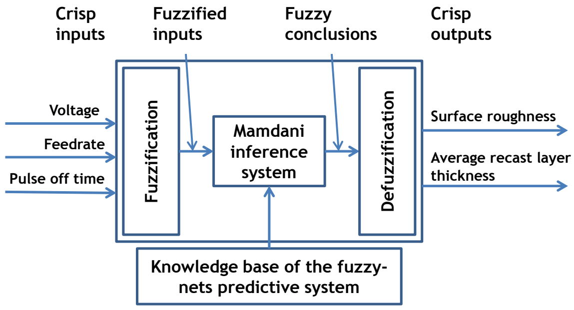

Fig. 5. Structure of the fuzzy-nets prediction approach.

The considered outputs for the offline fuzzy-nets prediction system are surface roughness and average recast layer thickness.

Based on experimental investigations, the main inputs for the offline fuzzy-nets prediction system are voltage, feed rate and pulse off time.

Such a prediction system is capable to simultaneously predict the performance of multiple VQCs for a given set of machining conditions.

The main components of offline fuzzy-nets prediction system are the Mamdani inference system [7] and fuzzy rule base.

The rules in the fuzzy rule base are generated from training experimental data and the missing rules are generated considering a multiple regression model (MRM).

The set of fuzzy rules provide a functional approximation of the relationships of the underlying system [8].

Since high average recast layer thickness implies necessarily high max recast layer thickness then it is necessary but not sufficient to select initial conditions with low predicted average recast layer thickness. The corresponding optimization problem is the following:

Minimize ARLT(V,P_{off},f)

Subject to:

$$\begin{cases} R_a \leq R_a^d \\ f \geq f^d \\ V_{min} \leq V \leq V_{max} \\ P_{off_{min}} \leq P_{off} \leq P_{off_{max}} \\ f_{min} \leq f \leq f_{max} \end{cases}$$

where ARLT(V,P_{off},f) is the value of average recast layer thickness predicted from the values of voltage (V), pulse off time (P_{off}), and feed rate (f), R_a is the value of surface roughness predicted from the values of V, P_{off}, and f, R_a^d is the desired value of surface roughness, f^d is the desired value of feed rate.

The combination of the fuzzy-nets prediction approach with an optimization method allows determining the set of initial conditions that minimize the predicted average recast layer thickness while fulfilling the requirements with respect to other performance indicators such as desired feed rate and surface roughness.

4.2 Online prediction and adjustment approach

For local surface defects such as surface lines and max recast layer thickness, an online prediction and adjustment approach as shown in Fig. 6 is a suitable solution. It is based on the high frequency sensing of features of the current and voltage signals in the discharge zone during the finishing machining to predict the defects, and the adjustment of the relevant VPPs to prevent the effective occurrence of the predicted defects.

The online prediction system consists of detecting the beginning of instability and in the case of prolonged instability adjusting the appropriate VPP.

Experimental investigation revealed that the main instability in W-EDM is related to the occurrence of a series of consecutive short circuits.

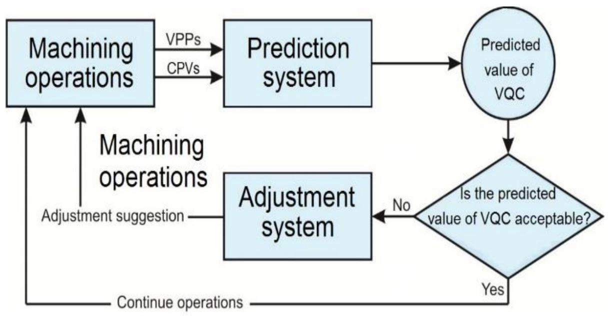

Fig. 6. Online prediction and adjustment system (adapted from [9]).

The main challenge for the application of the online prediction and adjustment system is to detect when a short circuit is about to occur in a high frequency process like the surfacing stage of WEDM. The main finding in [10] is the correlation between the increase in the spark frequency and the start of a short circuit. Hence the increase in the spark frequency is taken as an indicator for the start of a short circuit.

Since only prolonged short circuits provoke the occurrence of defects, an algorithm calculating the duration of the short circuit is proposed and the calculated duration is compared with the anticipation time. When the duration exceeds the anticipation time the adjustment of pulse off time is triggered to prevent the effective occurrence of the defects. The flowchart of the prediction and adjustment algorithm is shown in Fig. 7 in the Appendix.

The amount of adjustment of pulse off time is dependent on the initial conditions such as values of voltage, feed rate, pulse off time and type of wire. That is why a fuzzy-nets adaptive system is required to determine the amount of adjustment of pulse off time.

The structure of the online fuzzy-nets adaptive system is shown in Fig. 8.

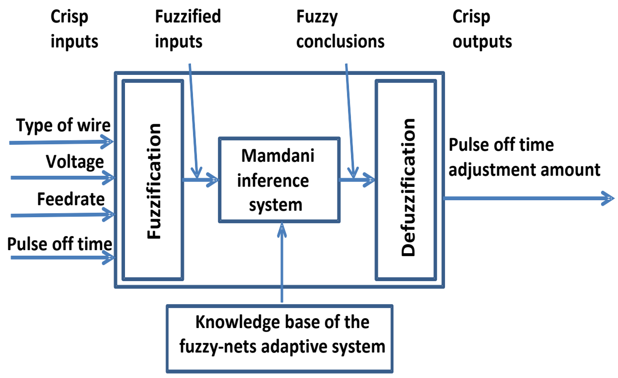

Fig. 8. Structure of the fuzzy-nets adaptive system

There is a need for intensive experimental campaign to collect training data required for the generation of the fuzzy rule base for the fuzzy-nets adaptive system.

4.3 Combined offline and online systems

The flowchart of the combined offline fuzzy-nets prediction system and online prediction and adjustment system is shown in Fig. 9 in the Appendix.

The offline prediction system intervenes before starting machining operations through selecting the best combination of values of process parameters to meet required levels of performance for part quality characteristics, and the online prediction and adjustment system intervenes during machining operations through monitoring machining conditions to predict any potential defect and take appropriate actions to prevent the effective occurrence of predicted defects.

5 Illustrative Example

Let us consider the training data in Table 3.

In this example we combine the fuzzy-nets prediction system with non-dominated sorting genetic algorithm-II (NSGA-II) from GA toolbox Matlab®.

Table 3. Characteristics of surface defects in WEDM

Run No.	*V* [V]	*f* [mm/min]	T_{off} [μs]	R_a[μm]	A*RLT* [μm]
1	110	6	1	0.46	1.49
2	110	6	6	0.59	1.95
3	110	6	11	0.61	1.73
4	110	11	1	0.5	1.74
5	110	11	11	0.7	2.06
6	110	16	6	0.73	1.08
7	150	6	1	0.62	1.5
8	150	6	6	0.66	1.33
9	150	6	11	0.73	1.69
10	150	11	1	0.64	4.25
11	150	11	6	0.73	1.31
12	150	16	1	0.64	1.4
13	150	16	6	0.74	1.12
14	150	16	11	0.89	5.07
15	190	6	6	1.12	3.02
16	190	11	1	0.75	6.13
17	190	11	6	1.05	4.02
18	190	11	11	1.06	4.72
19	190	16	6	1.02	4.97
20	190	16	11	0.99	1.03

Assuming a desired value of R_a of 0.7 µm and fixing the feed rate, the best combination of the process parameters is shown in Table 4.

Table 4. Best combination of process parameters

V [V]	*f* [mm/min]	T_{off} [µm]	R_a [µm]	*RLT* [µm]
149	16	2	0.67	1.3

6 Conclusion

In this paper we proposed a combined offline fuzzy-nets prediction system and online prediction and adjustment system to deal with the different types of surface defects occurring during the surfacing stage of W-EDM process.

We characterized the different types of surface defects into global defects and local defects and the appropriate approaches to each type of defect is indicated.

The combination of offline fuzzy-nets prediction system and online detection and adjustment system allows to handle several surface defects such as surface roughness, recast layer and occurrence of ‘surface lines’. Surface roughness and average recast layer thickness can be dealt with using the offline fuzzy-nets prediction system preferably combined with an optimization method and occurrence of surface lines and abnormally high recast layer thickness which are local phenomena influenced by the instability in the machining process can be handled using the online detection and adjustment system.

The combined offline fuzzy-nets prediction system and online prediction and adjustment system represents a significant contribution towards achieving near zero defect manufacturing in W-EDM, especially in successfully preventing, for the first time in the published literature, the occurrence of surface lines and marks.

The introduction of such an approach in the current practice of WEDM promises great benefits in applications with high reliability requirements such as the aerospace and biomedical sectors.

7 Acknowledgements

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8 Appendix

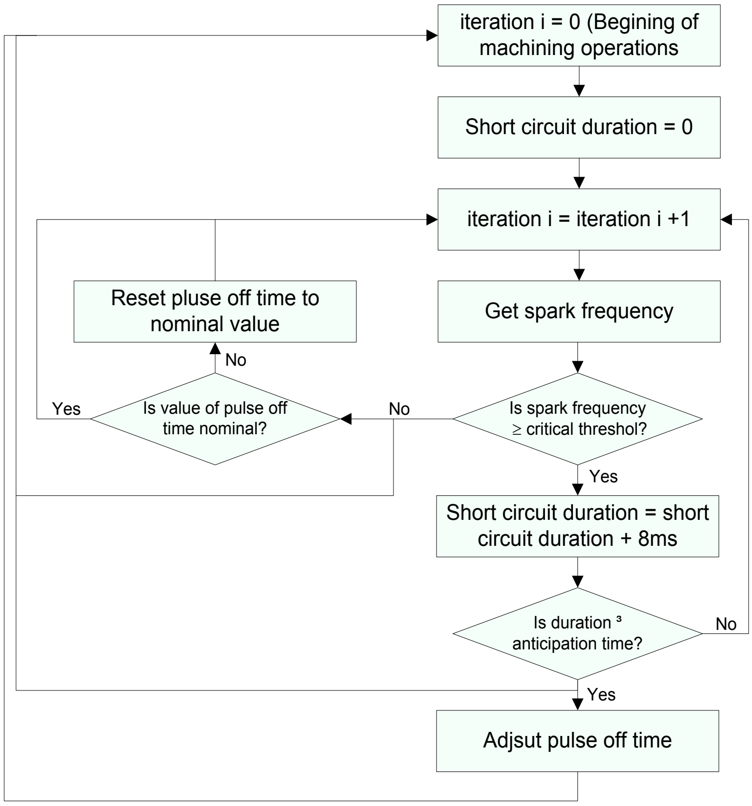

Fig. 7. Flowchart of online prediction and adjustment approach.

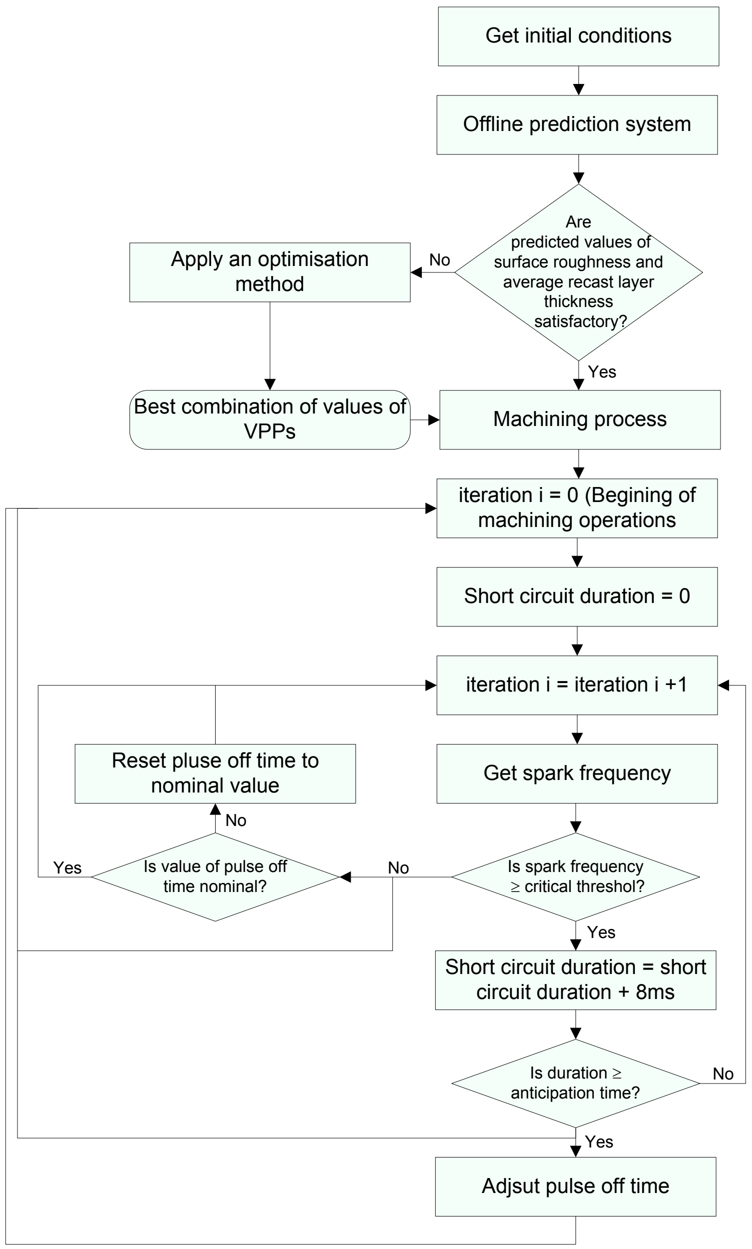

Fig. 9. Flowchart of combined online and offline systems.

Table 1. Input and output parameters for part quality prediction.

Parameter	Definition	Characteristics
Vital quality characteristic (VQC)	Part quality characteristic that shall be kept within specifications in order to assure zero-defect manufacturing	Parameters that need to be kept within certain range to ensure a desired quality level of the machined part
Vital process parameter (VPP)	Process parameter that affects identified VQCs of the product	These are the potential parameters to adjust in the case of deviation of VQC from the acceptable limits
Critical process variable (CPV)	Hidden process variable deemed to have significant impact on VQCs	These parameters allow to account for the machining process environment and capture the influence exerted by the unknown/ unmodeled factors on the VQCs

Table 2. Characteristics of surface defects in WEDM

Surface defect	Type	Related input parameters	Purpose
Surface roughness	Global	Vital process parameters	Minimization of surface roughness based on the initial conditions
Average recast layer thickness	Global	Vital process parameters	Minimization of average recast layer thickness based on the initial conditions
Max recast layer thickness	Local	Critical process variables	Minimization of max recast layer thickness based on the current machining conditions
Surface lines	Local	Critical process variables	Prevention of surface lines based on the current machining conditions