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A Review on Wire Electrical Discharge Machining of Advanced Conductive Materials

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Abstract

The evolution of advanced engineering materials, including superalloys, metal matrices, and ceramics, has led to advancements in the area of material engineering. These materials are not easily machined due to their properties such as rigidity, strength, hardness, and durability, and they face limitations in smooth machining with conventional machining. Machining of these materials is successfully achieved by using a non-conventional approach to machining. Wire electrical discharge machining (wire EDM) is an approach being used to create and manufacture three-dimensional (3D) complex structures and geometry with high cutting speed to achieve higher efficiency and productivity, good surface quality, and better accuracy of these advanced engineering materials. The article illustrates the evolution of the wire EDM process with various wire electrodes for advanced materials with an emphasis on the most acceptable machining conditions. The material removal rate (MRR), surface roughness (SR), kerf thickness (Kw), and the surface characteristics acquired during the machining were taken into discussion. The literature of work published on wire EDM shows that the research is directed towards more recent aspects of wire EDM for advanced materials in the field of optimization.

Disciplinary: Advanced Manufacturing and Technology.

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1 Introduction

Nowadays, Wire EDM is a well-known electro-thermal machining technique in which extraction of materials occurs from the sample due to the unstable electrical discharges generated between the workpiece and the moving wire as depicted in Figure 1. Wire EDM can rigorously cut the materials with a series of small discrete discharges with the existence of dielectric fluid around the machining area. The discharge generates extremely high-temperature estimates of around 8000 ^oC to 11700 ^oC and causes melting of material that leads to the extraction of material from the surface. The debris and waste generated from the machining zone are flushed out because of the continuous passage of dielectric fluid. The wire made of brass, copper, or tungsten is continuously travelling in wire EDM and must be loosened on one guide roller and wound on another guide roller to minimize or avoid the effect of material loss, which also contributes to tool wear. Efficient production capabilities, production reliability, stress-free and burr-free cutting, difficulty or even impossible to achieve the required surface characteristics of various materials by other machining methods, low cost, and high tolerances are the main advantages of wire EDM [1]. The paper incorporates the latest achievements in the field of the wire EDM process.

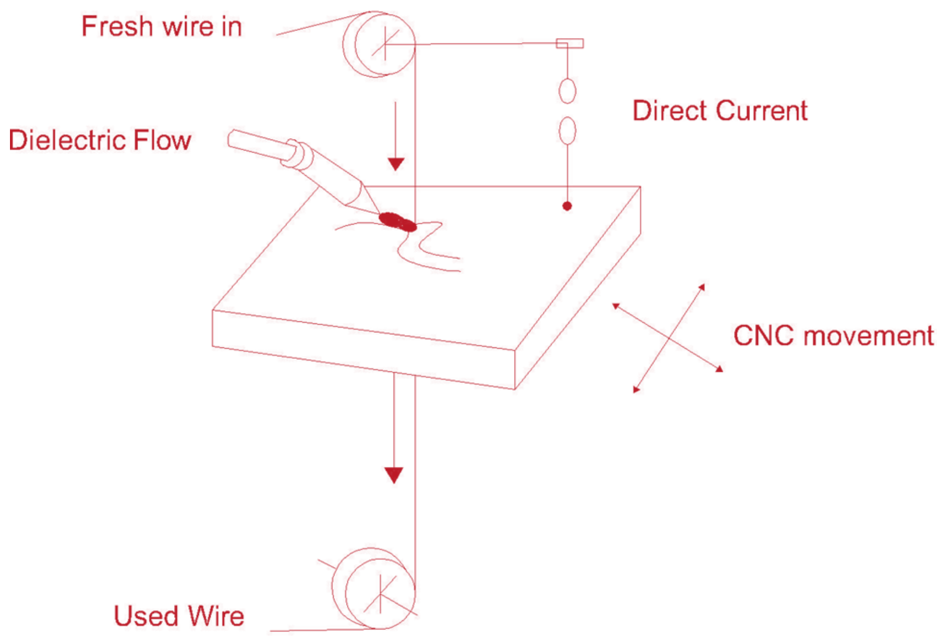

Figure 1. view of wire EDM cutting

The number of publications in the wire EDM process increases continuously day by day because of its flexibility in ensuring complex shapes for various conductive materials. Solid and low-stiffness materials can also be machined through wire EDM.

1.1 Aspects of Wire EDM Process

The Wire EDM process involves a vertically aligned running wire electrode and is supported by two guide subsystems. The upper wire guide support for the movement of fresh wire towards the workpiece can be achieved by steady movement in the horizontal plane as depicted in Figure 2. De-ionized water and electro-discharge machine oil are usually chosen as dielectric fluids due to their favorable properties, such as high fluidity and easy removal of debris or particles segregated from the electro erosive process. Other dielectric fluids are also studied and investigated in wire electro-discharge machining [2-4]. The moving wire speed through its axis must be larger to prevent the probable loss in diameter of the wire electrode owing to electrical erosion. The working gap between the wire and the workpiece is usually 0.01 to 0.05 millimeters and the size of the wire electrode varies from 0.01 to 0.5 millimeters. High-speed wire movement is used in the high-speed wire EDM technique for the machining of hard materials [5], [6], and requires tightness on the wire electrode to ensure its straightness and rectilinearity.

1.2 Wire EDM Components and Equipment

The wire EDM method employs a computerized numerical controlled worktable having an X- and Y-axis. The workpiece is held with a clamping mechanism on the worktable and a driving mechanism is utilized for steady movement of the wire electrode across the workpiece with tightness between upper and lower wire guides for straightness and rectilinearity, as depicted in Figure 2. The movement of the upper guide in Cartesian coordinates U and V axis is used to achieve the tapered surfaces driven by servo motors. The spark generator creates the pulses and makes it possible to validate and cause a series of discharges for the variability of various electrical parameters.

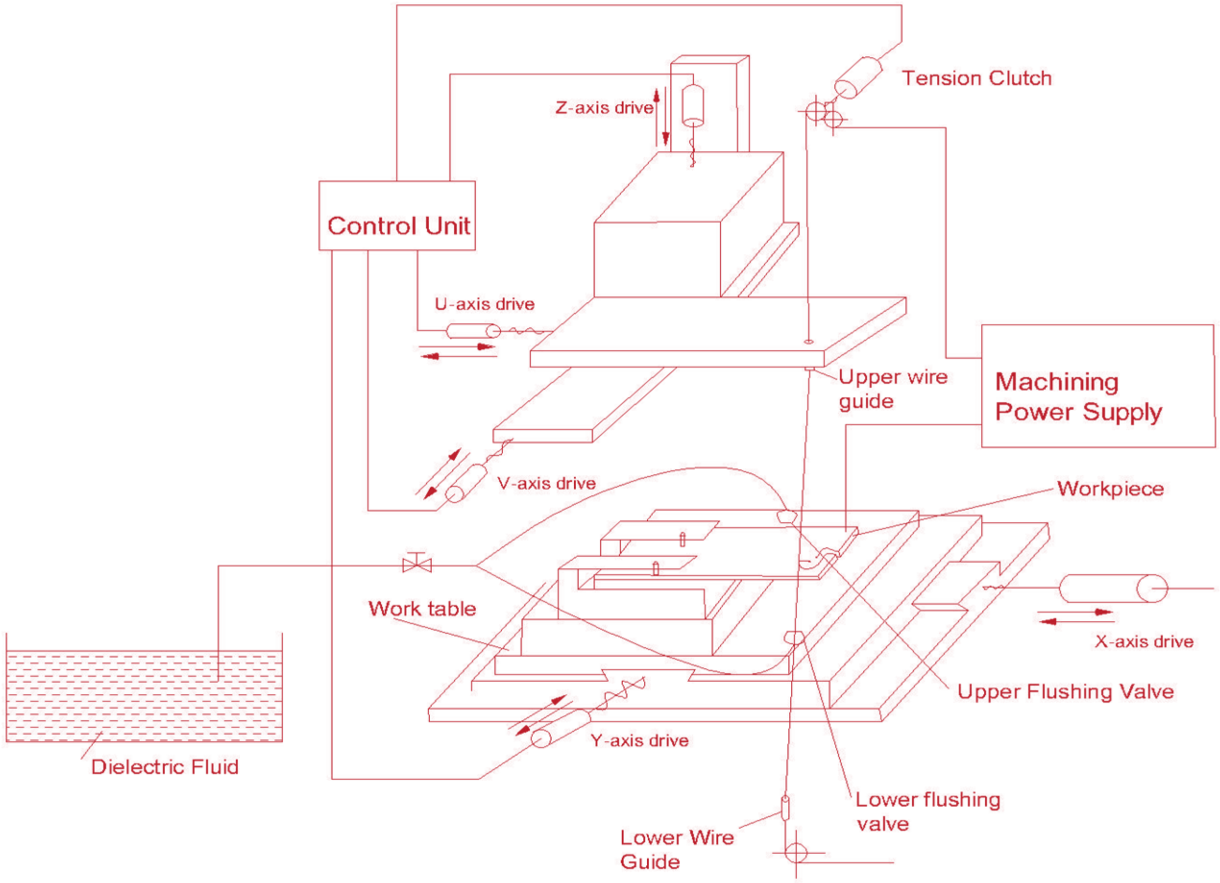

Figure 2: wire EDM machining zone and equipment.

The wire EDM machining system includes the major components as depicted in Figure 3. All conductive workpieces can be machined using the wire EDM process. The utilization of wire as a tool makes for a precise machining process. Dielectric fluid continuously flows from the tank to the machining zone where ionization occurs between the workpiece and the wire electrode.

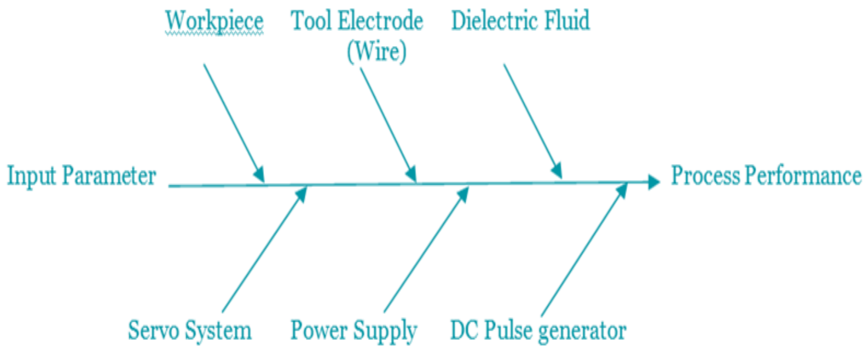

Figure 3. Major components of wire EDM

A servo device monitors the distance between the wire and the workpiece in order to precisely extract the material from the workpiece. Poor performance of the servo controller system causes undesirable speed of wire EDM machines and delays in ignition time. The conversion of alternating current (AC) from the main utility source into pulsed direct current (DC) requires a power supply to generate discharges at the machining gap. The wire EDM process can be categorized and described based on the flow of dielectric fluid to the machining region [7], Figure 4:

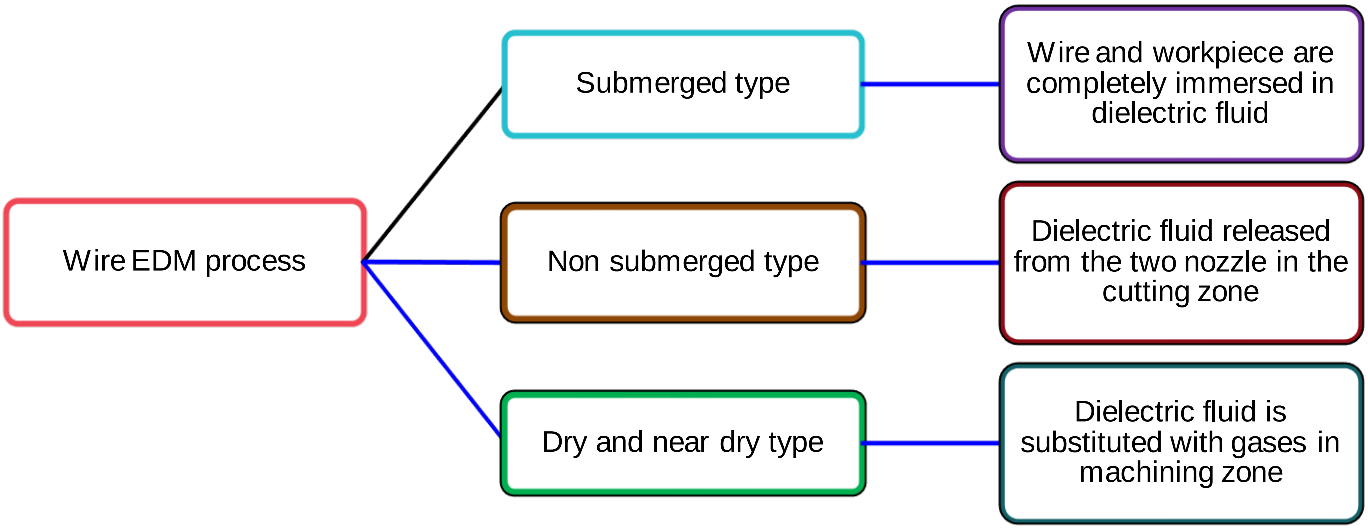

Figure 4: wire EDM process according to types of dielectric fluid flow.

Developments in numerical control (NC) subsystems have created a new era in the design of wire EDM equipment. Such tools and equipment have facilitated figuring out a wide range of obstacles in the short period required by the wire EDM machining process. The execution of computer numerical control (CNC) programs allows those who don't have expertise in this field to work efficiently.

2 Materials

Wire EDM can machine harder materials like tool steel, tungsten carbide, polycrystalline diamond compact, nickel-chromium alloy, titanium alloy, metal matrix composites (MMCs), and carbides with high wear resistance, high corrosive, high strength, and not favourable for conventional machining processes such as grinding, milling, and turning. Wire EDM machining of these materials has several applications, such as in the making of extrusion dies, the petrochemical industry, mould making, fuel injector nozzles, complex parts used in automotive, marine, and space aircraft engines, and turbine blades [8]–[13]. In comparison to electrically conductive machining of the workpiece, some wire EDM processes have also been reported on non-conductive materials and insulating ceramics [14-17].

3 Developments of Wire EDM Process

The first metal cutting using electricity was developed by Tilghman in 1889. Boris and Natalia Lazarenko in 1943 developed spark machining to develop the machining of electro-conductive materials. Electrical discharge machines have been successfully used to remove material from workpieces for almost twenty years. Some significant developments used for wire EDM are mentioned in Table 1. These developments were highlighted per the information obtained from the relevant literature [18-36].

Table 1. Major development of wire EDM process

No	Year	Research evolution
1	1889	Benjamin Chew Tilghman got a patent for innovation in metal cutting using electricity "Cutting metal by electricity".
2	1943	Boris and Natalia Lazarenko introduced the machining of electro-conductive materials.
3	1960	David H. and his team invented an optical line system that led to the development of CNC equipment.
4	1967	The primary wire EDM machine was introduced by a firm in the former Soviet Union and exhibited at a machine exhibition in Quebec, Canada.
5	1969	Agie (A Swiss Company) promoted a wire EDM machine at the European Machine Tool Exhibition in Paris.
6	1970	Unblended copper wires were utilised as wire electrodes in the 1970s.
7	1970	Brass wire was also used in the late 1970s in place of copper wire.
8	1980	Introduction of zinc coating on the copper wire.
9	1981	Introduction of zinc coating on brass wire.
10	1985	Wire electrical discharge grinding process suggested by Masuzawa.
11	1994	Rajurkar et al. examine the control system for spark frequency to calculate the height of the workpiece.
12	1997	Wire EDM with ultrasonic aide investigated and examined.
13	2005	Li et al. studied and investigated the high-speed wire EDM (WEDM-HS) process.
14	2006	Zhao and colleagues investigated the tangential feed for the wire electrical discharge grinding process.
15	2010	Sheu discussed and studied the twin wire electrical discharge grinding process.
16	2011	Muttamara et al. discussed micro EDM machining to reduce discharge energy induced by conductive layers for insulating ceramics.
17	2012	Cryogenically treated wire electrodes are used.
18	2013	Wire electrical discharge milling studied by Gotoh et al.
19	2015	Zhang studied and investigated the wire EDM process on nanocomposite ceramic materials with poly-vinyl alcohol in distilled water.
20	2015	Procedure for online recording of pulses in wire EDM at a middle speed based on machine learning and digital image processing.
21	2018	Highly precise wire control system to enhance the surface quality of the workpiece and geometric accuracy.
22	2019	Li et al. investigated the active supply of wire-electrical discharge grinding (AS-WEDG) to reduce wire variation and to enhance the aspect ratio of the microelectrodes.

4 Process Optimization and Modelling of Wire EDM Process

Nowadays, comprehensive research has been done on process optimization and modelling in the wire EDM process. A lot of researchers have studied and focused on improving and optimizing the wire EDM technique for advanced materials like superalloys, composites with ceramic reinforcement, and carbides. The major categories of superalloys and carbides are nickel chromium-based alloys, titanium alloys, nickel alloys, nickel-titanium alloys, boron carbide, and tungsten carbide, etc. The different designs of experiments and optimization processes have been used to construct the mathematical model for performance in the wire EDM process. The Taguchi method, response surface analysis, and regression analysis are exhaustively used by many researchers, but nowadays, modern approaches like artificial neural network (ANN), fuzzy method, particle swarm technique, grey wolf optimizer, teaching-learning based optimization, etc. have been used in developing models.

Table 2. Important findings and effects of various input parameters on wire EDM for different materials

No	Author	Material and Methods	Finding of study
1	Kapgate et al.(2013)	The sequential classical method is used to experiment to cut Al/SiC10% metal matrix composite material into different shapes and optimize the parameters using the Mini-max principle and linear programming to enhance the output performance.	The combined effect of parameters using dimensionless π term suggests and improves the productivity and helps to maintain the removal rate and roughness by changing one parameter [37].

No	Author	Material and Methods	Finding of study
2	Marigoudar and Sadashivappa (2013)	The Zn-Al alloy reinforced with silicon carbide (SiC) in powder form is used to analyze the performance of wire EDM. The Liquid metallurgy technique was used to prepare the ZA43/SiCp composite. Analysis of variance gives the most significant parameter for the selected response.	The increase in silicon carbide content in the composite metal matrix causes a significant decrease in the removal rate and higher surface roughness. The favorable effect on MRR is defined by the current and pulse duration time [38].
3	Goswami and Kumar (2014)	Machining of NIMONIC 80A (nickel-chromium alloy) material was conducted on wire EDM for MRR, surface integrity, and wire wear ratio using Taguchi OA design of experiments and optimized through multi-response technique grey relational analysis (GRA). Machined surface microstructure analysed using a scanning electron microscope (SEM).	At the 95% significance level, pulse duration and pulse interval are found to be the most favorable parameters for material removal rate. Excessive discharge energy causes large craters and can be seen in the microstructure. A high discharge energy level causes the surface recast layer to be thicker as compared with a low discharge energy level [39].
4	Kumar et al. (2015)	Experimental evaluation on wire EDM of Monel-400 (nickel alloy) material with four parameters examined and optimized two responses: machining rate and surface roughness.	The impact of variable factors on material removal is shown by a response surface graph. The quadratic model is adapted and found suitable for material removal using variance analysis, while the two interaction factors (2FI) model is recommended for surface roughness [40].
5	Caydas and Ay (2016)	Machining influence of input factor on wire EDM of Inconel 718 superalloy evaluated and examined for surface roughness, cutting width, and recast layer characteristics. The Analysis of variance technique (ANOVA) and regression analysis are used for model development to describe the effect of parameters on the quality of wire EDM.	Current and pulse duration are found to significantly affect the surface roughness by using ANOVA. The results drawn from the model show strong robustness with respect to the coefficients Ra, RLT, and Kw [41].
6	Goyal (2017)	Cryogenic treated zinc coated and normal zinc-coated wire electrodes were used to assess the influence of variable factors on wire EDM of Inconel 625 superalloys. L18 orthogonal design of experiments is used for designing experiments. Surface characteristics of machined surfaces are analyzed using a scanning electron microscope.	The cryogenically treated tool improves the rate of material removal and demonstrates good surface integrity than standard tool electrodes. The rate of material removal is also substantially improved by pulse duration and pulse interval. Increased pulse duration and current decrease the surface quality and increase the roughness [42].
7	Unune and Mali (2017)	Micro wire EDM has evolved into a micromachining process to fabricate micro features. But, the poor surface quality and low machining rate limit the wide application of this process. The performance of microwire EDM of Inconel 718 using a box Behnken design of experiment was analysed statistically for the output responses.	It has been observed that capacitance has a major effect on the rate of material removal and cutting width. The low-frequency vibration enhances machinability characteristics due to increased flushing conditions and decreased workpiece and wire electrode adhesion [43].
8	Gołabczak et al. (2019)	The assessment concerned the effect of wire EDM and vibratory abrasive machining on the geometrical structure of hard materials like Titanium 5553 b alloy, Inconel-617, Hastelloy-X, and AZ-31 Magnesium alloy. Optimal electric parameters are used in the machining of hard materials for final cubic and cylindrical samples and polished using circular vibratory finishing technology.	The results suggested a reduction in the structural morphology of these alloys when gradually increased in voltage and current intensity. Micro craters and weld penetration are also seen in the morphology of the surface structure caused by spark discharges. It also suggested that Vibro abrasive technology is suitable for polishing very hard materials because of its complicated geometry [44].
9	Mostafapouraand Vahedi (2019)	The effect on MRR, kerf thickness, and SR of the input parameters of the wire EDM during machining of magnesium alloy evaluated and examined the machinability characteristics and behavior of materials with high thermal conductivity during machining using the response surface methodology. The changes in microstructure and surface layer were evaluated using SEM and EDXS analysis.	The results promise that MRR in the machining of magnesium alloy is significantly higher than in hard materials. Minimum microcracks and non-damaged surfaces observed using a scanning electron microscope show the capability of producing a good machined surface using Wire EDM [45].

No	Author	Material and Methods	Finding of study
10	Mouralova et al. (2020)	A Comprehensive design of experiments is used to monitor the different input factors in the machining of NIMONIC C 263 superalloy to enhance efficiency. Optimal results were drawn for the machining accuracy and surface quality and analysed the lamella using a transmission electron microscope (TEM).	Machining of superalloy accomplishes both by reducing machining time, creating financial savings, and improving machined surface quality. The morphology analysis verifies the absence of any cracks or burnt cavities in machined samples. TEM lamella analysis showed in detail the composition at the atomic level [46].
11	Dzionk and Siemiątkowski (2020)	The study evaluates the effect of input parameters, including dielectric pressure, pulse duration, on the machining of Inconel 617 using wire EDM. Box–Behnken design scheme used to design the experiments for dimensional accuracy, surface characteristics, and MRR.	The MRR is significantly influenced by the pulse duration during the machining. The debris and residue particles are effectively removed by flushing them. There is no change in peak and valleys due to the possible setting of input parameters, but some changes in waviness structure are perceived when compared with the longitudinal and transverse directions of the cutting direction [47].

Using single objective optimization or multi-objective optimization approaches, the combination of input factor values impacts process performance. As the wire EDM is governed by various input variables like pulse duration, discharge current, voltage, and wire-speed, etc., small variations in these input factors affect the process performance of machining. MRR is a significant output response that affects the productivity of any process. The increase in MRR caused the economic benefit of using wire EDM for any organization [48]. Mechanical properties like fatigue strength are improved in the manufacturing of titanium alloys for space and aircraft applications by using wire electrical discharge machining [49]. Table 2 shows some research findings on the design of input parameters, approaches to assessing the influence of these input factors, and modelling of the wire EDM process.

5 Conclusion

This review emphasizes elementary concepts, developments, challenges, and opportunities in the wire EDM technique. A brief study emphasizes the interest of researchers in the investigation, evaluation, application, modelling, and optimization of the wire EDM process. The general objective of many researchers is to improve the performance and proficiency of wire EDM for different advanced materials and also materials characterized by low electrical conductivity. Some investigations to enhance the components of the wire EDM system. Many researchers have focused on characterizing the input variables in the machining process. The dimensional accuracy, MRR, surface integrity, and process productivity have all been addressed as output responses. The mathematical tools were developed to optimize and study the effectiveness and impact of input parameters on output performance.

The review reveals a considerable rise in published articles in the last few years that address topics connected to the wire EDM process. In the years ahead, this tendency is anticipated to continue. The desirability of exploring the possibility of using new variations in wire EDM and machining of some advanced and hard materials that can be worked out in the future is expected to be significant in the coming days. Further attempts at optimization are also predicted with the consideration of Industry 4.0 stage requirements.

6 Availability of Data and Material

Data can be made available by contacting the corresponding author.

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