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Machining of Stainless Steels and Alloys Using Non-Traditional Machining Processes

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Abstract

Stainless steels and alloys are characterized primarily by their corrosion resistance, high strength, ductility, etc. used for various advanced applications like automotive and aerospace, sugar refineries, construction materials, etc. Many advanced high-speed machineries /systems need fine quality of parts to provide good performance in its working conditions. The machining of stainless steel and its alloys is of interest, because, of its excellent mechanical properties. Stainless steels and alloys are machined generally by traditional machining processes. But complex shapes and features on products are difficult task with the use of traditional metal cutting techniques. To machine the advanced materials to produce high dimensional accuracy and generation of intricate shapes in difficult-to-machine materials like stainless steels and alloys, nontraditional machining (NTM) techniques are now attractive the viable choices. To attain improved machining performance of the NTM processes, it is always necessary to find the optimal combinations of various process input parameters of those processes. In the present chapter, some aspects of machining of stainless steel and alloys using NTM processes such as electric discharge machining (EDM) and wire EDM, are discussed and some concluding remarks have been drawn from the study.

Keywords: stainless steels and alloys, nontraditional machining, EDM, wire EDM

1. Introduction

With the increased industrial and technological growth, materials exhibiting excellent strength, hardness, stiffness to strength ratio, good corrosion resistance properties have found wide applications particularly in aerospace, nuclear engineering, navel, marine, space technology, tool industries [1], etc. The advanced materials include stainless steel, refractory materials and

its alloys, carbides, ceramic alloys, glass and fiber-based composites, etc. Stainless steel and its alloys got immense importance for variety of advanced applications. Most of stainless steels and its alloys (SS&A) treated as difficult to machine materials. Machining of SS&A using traditional methods like turning, milling, drilling, grinding, etc., cannot preferable, because of low cutting speeds and material removal rates. And it's difficult to find cutting tools to cut these type materials. Machining of stainless steels and its alloys is an important research area for industrialists.

Stainless steel materials gained much important materials for industries at the beginning of twentieth century. Stainless steels are defined as steel alloys described mainly by its corrosion resistance, high strength, high ductility and high chromium content present.

- Steel is one of the most attractive and widely used products in the world for various applications.
- Currently, the steel industry is plays vital role for process of change.
- Because of continuing procedural, technical and economic growth, the manufacture and use of steel is becoming increasing
- The use of steel continuously gaining its share of world-wide over the last three decades

French scientist Berthier was found the iron-chromium alloys which resist to certain acids in early eighteenth century. Then after Brustline another French scientist identified the importance of carbon (C) percentage levels and chromium (Cr) levels. In 1904, Leon Guilet [2] had invented the martensitic and ferritic SS-alloys series (i.e. 410, 442, 446, and 440 C) and Fe-Ni-Cr austenitic alloy series (300 series of SS). Various researchers conducted research investigations to improve the mechanical properties of stainless steels and its alloys with addition of different supplements like Cr, Ni, C, Mo, manganese, silicon, titanium, molybdenum, aluminum, sulfur, phosphorous, nitrogen, etc., to iron (Fe). Monnart and Eduard Maurer invented the stainless steel and austenitic stainless steel in the year of 1911 and 1912 respectively [3], with improved corrosion resistance property. The free machining stainless steels with addition of 15% sulfur was introduced to the world in the year of 1928. Stainless steels with 15% sulfur were called as martensitic 416 stainless. Then after sulfur and phosphorous were both added to make the austenitic stainless grades of 303 [4]. Maurer and Brearly described the advantages of stainless steel for industrial applications [5].

These alloys are milled into coils, sheets, plates, bars, wire, tubing, etc., to be used extensively in cookware, cutlery, surgical appliances, industrial equipment (e.g., in sugar refineries), automotive and aerospace operational alloys, as a construction material, etc. stainless steels and alloys are widely used in storage tanks for transporting of various liquid based materials like orange juice, apple juice and other oil-based products, due to its corrosion resistance and antibacterial properties. These materials are also used in commercial kitchens, food processing plants etc.

The applications of stainless steels and its alloys have been increased enormously over last 30 years in various engineering related fields because of their excellent materials properties such as high strength, high temperature strength, high corrosion resistance, oxidation resistance, etc. These materials are treated as difficulty to machine materials because of low thermal conductivity, high coefficient of thermal expansion, high ductility, and high work-hardening rate, etc. Low thermal conductivity nature in these materials increases in tool temperature during

machining, which leads to reduced tool life and tolerances of work-piece. Chip formation is severely affected due to high work-hardening rate and low thermal conductivity. High ductility nature has creates built-up edge on cutting tool edge and propagates vibration and chatter finally it have detrimental effects on quality of machined surface.

It is difficult to find adequate cutting tool materials to machine the advanced materials like stainless steel and its alloys using traditional machining processes. The new cutting tools along with advanced machining methodology called non-traditional machining (NTM) have been developed to machine the newly developed materials like stainless steels, ceramics, high strength polymers, composites and other alloy materials. These processes can capable of machine a wide spectrum of difficult-to-cut materials irrespective of their hardness. The important NTM processes are electric discharge machining (EDM), wire EDM, electron beam machining (EBM), ion beam machining (IBM), etc. It is necessary to conduct the NTM processes in optimum manner to enhance machining performance.

In the present paper reviews the research work carried out from the spin-off from the NTM processes to the development of NTM processes related to thermal energy-based techniques like EDM and WEDM. It reports on the research work involving the optimization of process parameters which expected to influencing the machining performance and productivity. The paper also highlights the important process parameters for performing the above said processes when machining of stainless steels and its alloys.

2. Machining of stainless steel and alloys by NTM processes

Machining or metal cutting is one of the important manufacturing processes in which excess or unwanted material is removed by cutting tool / electrode tool with or without physical contact with the work-piece. The classification of the machining processes is shown in **Figure 1**. From **Figure 1**, one notified that machining process is categorized into two types: traditional machining (TM) processes and non-traditional or non-conventional machining (NTM) processes. In traditional machining processes, material removal has carried out by using sharp edge cutting tool with physical contact with the work material. Tool material wear, generation of vibrations, difficulty of machining hard materials, impossible or uneconomical to produce complex shapes on parts, minimized tool life, decreased production rate and increased production costs are some of the limitations associated in TM processes because of physical contact with the work-piece. To overcome the limitations of TM techniques, NTM are developed. NTM methods applied successfully where work-piece surface is too hard, strong, flexible to resist cutting forces, difficult to clamp, to create complex shapes with both internal and external profiles, to produce fine surface finish and tolerances, residual stresses are unacceptable for materials.

In NTM processes, physical tool may not present, no chip formation may take place, cutting tool need not to be harder than work material and it do not necessarily apply mechanical energy. NTM methods are classified according to usage of energy for machining are chemical energy, electrical energy, mechanical energy, electrical energy, thermal energy, etc. Thermal energy-based processes are plays important role in metal cutting industries. In thermal energy-based techniques, material

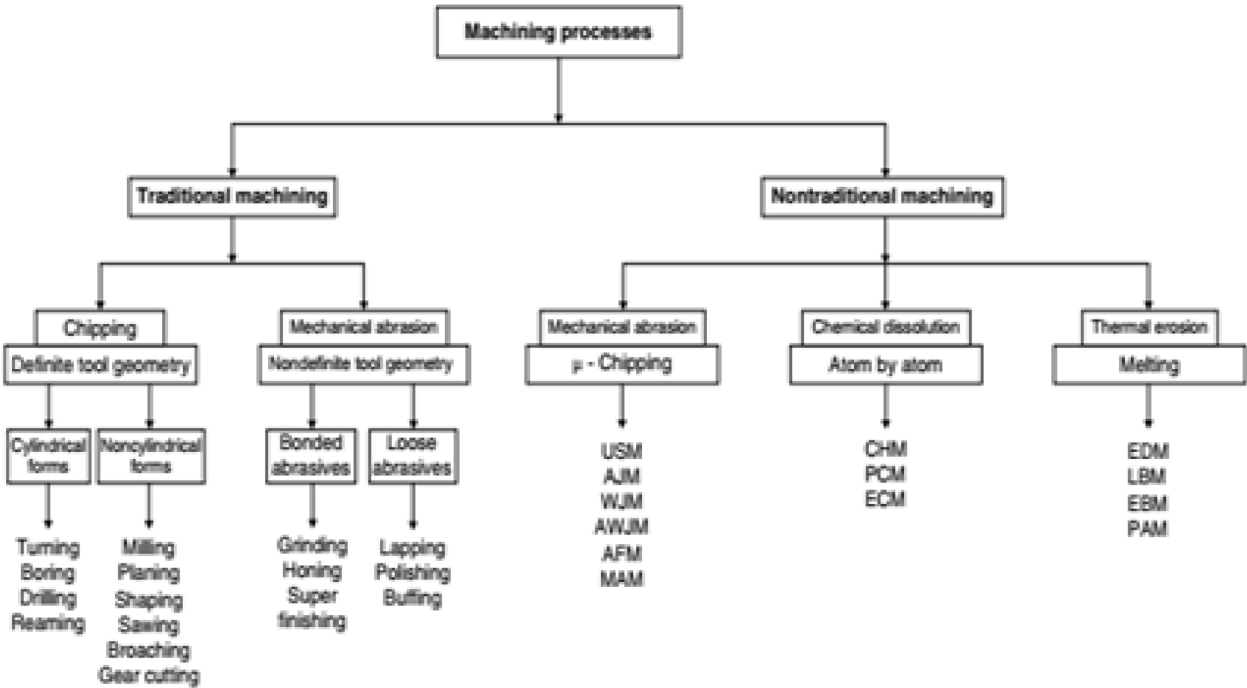


Figure 1. Classification of machining processes [2].

removal processes based on thermal energy are characterized by very high local temperatures—hot enough to remove excess material by fusion or vaporization method. Because of the high temperature generation during metal removal process, these processes cause physical and metallurgical damage to the newly generated surface of the work material. The two main processes in this category are (1) electric discharge machining and (2) wire electric discharge machining. These processes can be used only on electrically conducting work materials.

2.1. Electric discharge machining (EDM)

Electric discharge machining (EDM) is one of the nontraditional processes most widely used in mold, die, aerospace, automotive industry and surgical components for generating intricately shaped, and mold cavities on difficult-to-cut electrically conductive materials like high strength, temperature resistant (HSTR) alloys [6–10]. In EDM, mechanical stresses, chatter and vibration during machining can be eliminated because electrode tool does not make any direct contact with the work-piece [9].

An EDM setup is illustrated in **Figure 2**. The shape of the finished work-piece surface is replica of formed electrode tool. The EDM process conducted in the presence of a dielectric fluid, which makes a path for passing each discharge current to the fluid. So, fluid becomes ionized in the gap. The discharges are generated by a pulsating direct current and power supply connected to the work and the tool. The sparks occur across a small gap between electrode tool and work-piece surface. There are hundreds of electrical discharges generated during machining process and every discharge energy may form a specific surface integrity on the part which results in creation of surface texture by overlapping craters [11].

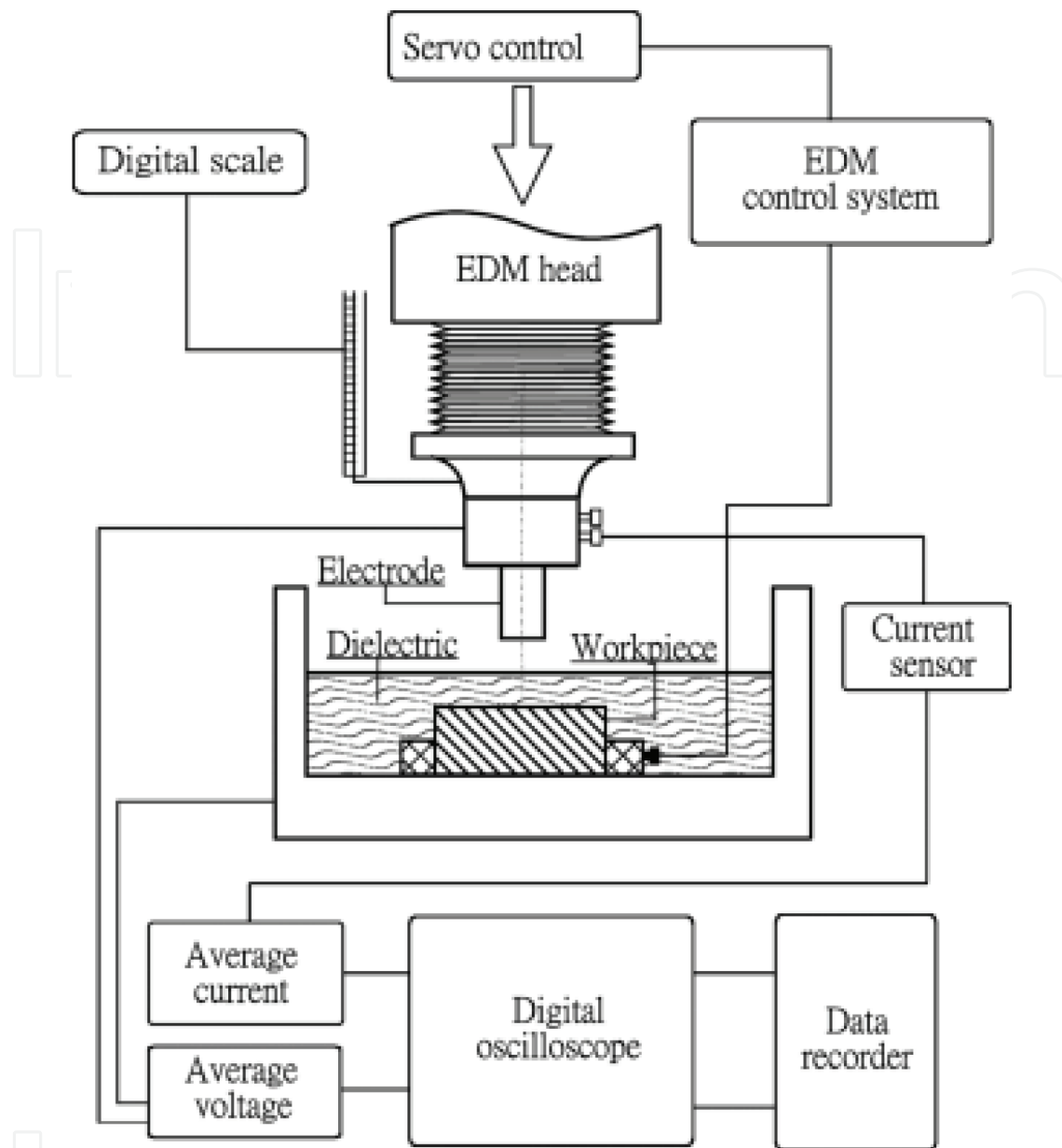


Figure 2. EDM process [20].

The mechanism behind the material removal in EDM is complex and difficult to understand and thus it is difficult task to formulate the relationships between the input and output parameters and to predict the better EDM performance [9, 12, 13]. The inappropriate selection of control parameters in EDM process may result in poor machining performance, short-circuiting between the electrodes or even work-piece surface may damage thereby reducing the productivity and affecting the quality. Due to high capital and manufacturing costs, these processes need to be operate economically and predictably to obtain machining economics. Identifying optimal set of parametric conditions is necessary to optimize production rate, machining time, lower material waste and costs, [8, 14] etc. Analyzing, modeling and optimizing EDM process may useful to improve the performance characteristics of EDMed parts.

Literature survey has been done to review and study the machining of stainless steels and its alloys in EDM process. The details of the literature survey are given as follows:

The maraging steel is a high strength material which exhibits resistance to corrosion oxidation in its working. Machining of maraging steels by using traditional machining process is difficult, because, of its high hardness. Ruma et al. [1] had experimented the EDM of maraging steel material to investigate the influences of EDM parameters on output responses. Researchers optimized the multi-performance characteristics using teaching learning-based optimization (TLBO) and genetic algorithm (GA). Authors mentioned that selection of optimum parametric conditions essential for conduction of EDM process effectively and economically. The 17-4 PH steels widely used for aerospace and die manufacturing, Chandramouli and Eswaraiah [6] had experimented EDM of 17-4 precipitation hardening stainless steel material to evaluate the influences of input parameters: peak current, pulse on time (T_{ONN}), pulse off time (T_{OFF}) and tool lift time on output response: material removal rate (MRR) and surface roughness. Researchers had studied, analyzed and optimized the EDM process to fine quality parameter (R_a) and qualitative factor, MRR when machining of 17-4 PH steels. Die steel materials are most widely used for industrial purposes and machining of these materials are important area of research. Banh et al. [14] presented a research work related to optimize the quality characteristics of die steel materials such as SKD61, SKD11 and SKT4, in titanium powder mixed EDM process. Researchers had been considered workpiece material, tool material, polarity, T_{ONN} , current, T_{OFF} and powder concentration as input parameters and MRR, tool wear rate, surface roughness, and microhardness surface, as quality responses. They stated that input parameter selection is very crucial for obtaining better performance characteristics. Electric discharge machining with powder mixed has improved its performance significantly. Priyaranjan et al. [15] had made an experimental analysis to evaluate the relationship between process parameters like pulse current, pulse duration, T_{OFF} and dielectric pressure, and performance characteristics of MRR, electrode wear rate and taper angle of the hole of AISI 329 stainless steel in EDM process. The stainless-steel grade of 329 which commonly found for several industrial applications like heat exchangers, chemical tanks, pressure vessels, etc. Investigators had been effectively optimized output responses by controlling input parameters. They stated from their work that properties of electrode and work-piece material influences much for EDM when machining of AISI 329 stainless steel.

Pradhan and Das [7] had made experimental analysis and developed predictive models for optimizing MRR by considering discharge current, pulse duration, duty cycle, and voltage as input machining parameters in EDM of AISI D2 tool steel. They identified from their study that MRR of D2 tool steel in EDM is highly effected by input parameters. The MRR is increase with increase of discharge current, duty cycle, and voltage whereas pulse duration is most significant for MRR. Janmanee and Muttamara [16] have performed the experiment on EDM to improve the drilling performance of stainless steel AISI 431 using brass tube electrode. They determined that MRR increases with increase of servo rate, while the taper of the hole increases with increase of electrical current and servo rate. Panda and Bhoi [10] worked on analyzing, modeling and optimization of MRR for die steel in EDM process using ANN. They considered pulse current, pulse voltage and duty factor as input parameters. Researchers had been developed relationships between input parameters and MRR effectively. AISI P20 steel is using as a tool for injection molding, Amorim and Weingaertner [17] had made an

experimental research work based on the EDM of AISI P20 tool steel. They analyzed the significances of control parameters on MRR, volumetric relative wear (VRW) and surface roughness of P20 tool steel material. Kumagai et al. [18] had explored the effects of electrode material on narrow deep holes in drilling of steel blocks. Jain [19] carried out the experimental analysis to identify the effects of pulse time, diameter of tool and depth of penetration on output responses of EDM of high-speed steel (HSS). He mentioned from his study that EDM is very efficient to make blind holes in HSS material. Some more publications related to the EDM of stainless steels and alloys are given in **Table 1**.

2.2. WEDM

Wire electrical discharge machining (WEDM) is a non-traditional machining process that is widely used to machine high strength materials. It is one form of EDM as mentioned earlier.

S. No	Reference	Work material	Process parameters	Output responses	Impact
1	Ubaid et al. [21]	Stainless steel 304	Current, T_{OFF} , T_{ON}	MRR, EWR, VEW	Current and T_{OFF} are most significant
2	Majumder [22]	AISI 316 LN stainless steel	Current, T_{OFF} , T_{ON}	MRR, EWR	All parameters are significant
3	Priyaranjan et al. [15]	AISI 329 stainless steel	Current, T_{OFF} , pulse duration, dielectric pressure	MRR, EWR, taper angle of hole	Current and pulse duration are significant for brass electrode; T_{OFF} is significant for copper electrode
4	Dastagiri and Kumar [23]	Stainless steel and En41b steel	Current, V, T_{ON} and duty factor	MRR, R_a and hardness	All the parameters are significant for both the materials
5	Shashikant et al. [24]	EN41 steel	T_{ON} , T_{OFF} , V and discharge current	R_a , R_q , R_{sk} , R_{ku} and R_{sm}	Current is significant for surface roughness
6	Shashikant et al. [25]	EN19 and EN41	T_{OFF} , T_{ON} , V and discharge current	MRR	Current is significant for MRR of both the materials
7	Rajmohan et al. [26]	Stainless steel 304	Current and voltage, T_{OFF} , T_{ON}	MRR	Current and T_{OFF} are significant for MRR
8	Faisal and Kumar [27]	EN 31 steel	Current, T_{ON} , T_{OFF} , gap voltage	MRR and R_a	Current is significant for both the responses
9	Behera et al. [28]	AISI 304 stainless steel	Current, T_{ON} , flushing pressure	MRR	Current is significant for MRR
10	Kumar et al. [29]	AISI H13 die steel	Sparking voltage, discharge current, T_{OFF} , T_{ON} , dielectric fluid, workpiece material H13 hot die steel: hardened and tempered	Micro-hardness, R_a	All parameters have considerable effects on responses

T_{OFF} = pulse off time; T_{ON} = pulse on time; EWR = electrode wear rate; VEW = volumetric electrode wear; MRR = material removal rate; R_a = surface roughness.

Table 1. Literature survey related to machining of stainless steels and alloys in EDM.

WEDM is very complex machining process which used to create high complicated shapes such as tapers, involutes, parabolas and ellipses [30] on hard materials like stainless steel, nitronic austenitic stainless, beryllium copper and titanium, ceramics, metal matrix composites [31], etc. The WEDM process involves a material erosion mechanism by pulsing of direct current between the wire electrode and work piece [32]. WEDM uses electro- thermal based energy to cut electrically conductive material(s). WEDM uses a thin continuously moving electrode in the form of wire in the range of 0.050–0.35 mm [33]. In WEDM, unwanted material is removed using series of discrete discharge currents between the wire electrode and the work material in the presence of a dielectric fluid [34]. Each discharge passed to the dielectric fluid and it becomes ionized in the gap resulted in generation of extremely high temperatures, therefore work-piece surface is melted and removed. The machined surface is cleaned by dielectric fluid by taking removed chip along with it. The schematic diagram of WEDM is shown in **Figure 3**. The melting point temperature of the work material is very important factor for WEDM process rather than its strength and hardness of the material [35].

WEDM is special from of EDM which enables to create very complex shapes very easily by using thin wire as electrode as mentioned above. Here, literature survey has been made to review and investigate the parts produced by WEDM of stainless steels and alloys, those details are given as follows:

DC53 is cold die steel improved from familiar cold die steel SKD1, made from daido steel. Machining of DC53 die steel is an important task. Kanlayasiri and Boonmung [35] presented an investigation of the effects of machining variables: pulse-peak current, T_{ON} , T_{OFF} and wire tension on the surface roughness of DC53 die steel material in wire-EDM process. Shahali

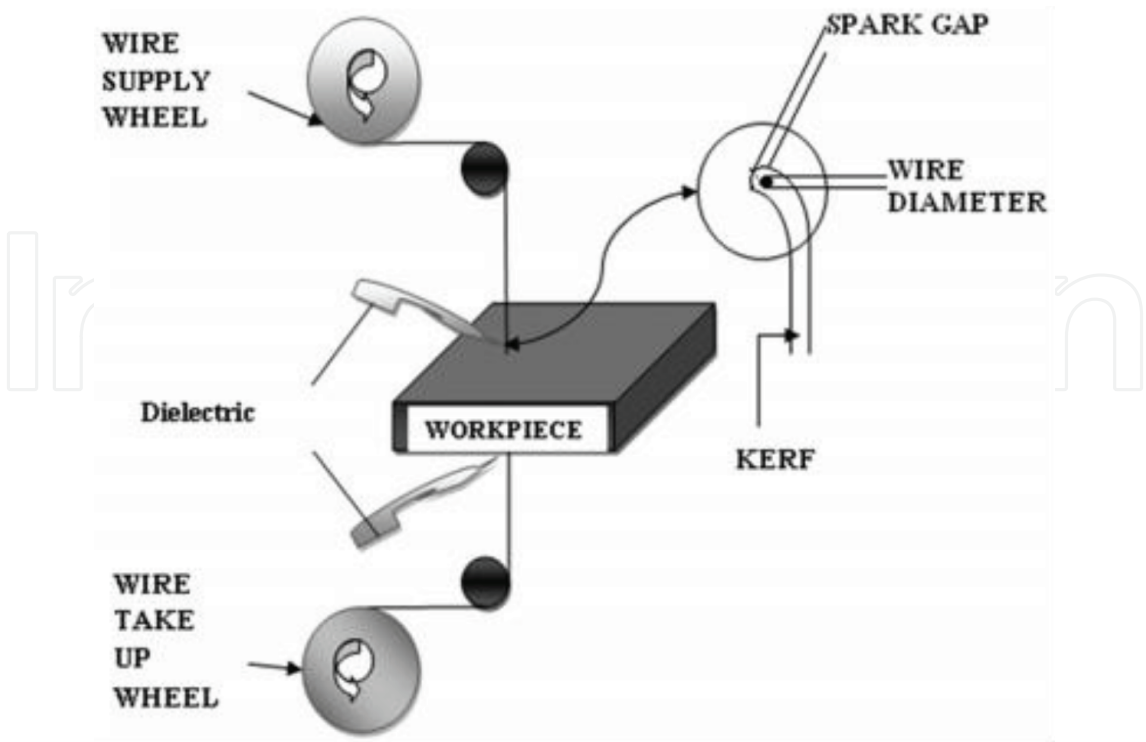


Figure 3. WEDM process [33].

S. No	Reference	Work material	Process parameters	Output responses	Impact
1	Majumder et al. [41]	Indian reduced activation ferritic martensitic (RAFM) steel	pulse current, T_{OFF} , T_{ON} , wire tension	Cutting speed and R_a	All parameters have significant effect on both the responses
2	Giduturi and kumar [42]	H-13 tool steel	Wire tension, wire feed, T_{OFF} , T_{ON} , servo voltage, peak current	MRR and R_a	All parameters have significant effect on both the responses
3	Pamnani et al. [43]	DMR249A steel	Current, torch speed, arc gap	Depth of penetration	Current and torch speed have significant effect on depth of penetration
4	Choudhuri et al. [44]	AISI stainless steel-316	Servo gap set voltage, T_{OFF} , T_{ON} and wire feed rate	MRR, R_a and lower wire consumption	Servo gap set voltage is significant for all the responses
5	Sudhakara and Prasanthi [45]	Powder metallurgical cold worked tool steel	T_{ON} , T_{OFF} , Peak current, spark gap set voltage, wire tension, water pressure	R_a	T_{ON} parameters has the significant effect on R_a
6	Reddy et al. [46]	P20 die-tool steel	Bed speed, T_{ON} , T_{OFF} and current	R_a and volumetric material removal rate	All parameters have significant effect on both the responses
7	Manjaiah et al. [47]	D2 steel	Servo voltage, wire feed, T_{ON} , T_{OFF}	MRR and R_a	T_{ON} and servo voltage have significant effect for both the responses
8	Tosun et al. [48]	AISI 4140 steel	pulse duration, open circuit voltage, wire speed dielectric flushing pressure	R_a	open circuit voltage and pulse duration have significant effect on R_a
9	Ugrasen et al. [49]	Modified AISI 420 steel	T_{ON} , T_{OFF} , current, bed speed	R_a , VMRR, accuracy and EWR	All factors significantly affecting the all responses
10	Sudhakara and Prasanthi [50]	VANADIS 4E (powder metallurgical cold worked tool steel)	T_{ON} , T_{OFF} , peak current, spark gap set voltage, wire tension, water pressure	Dimensional deviation	T_{ON} , T_{OFF} , peak current, water pressure have significant effect on dimensional deviation

VMRR = volumetric material removal rate; T_{OFF} = pulse off time; T_{ON} = pulse on time; EWR = electrode wear rate; VEW = volumetric electrode wear; MRR = material removal rate; R_a = surface roughness.

Table 2. Literature survey related to machining of stainless steels and alloys in WEDM.

et al. [36] made an experimental analysis to identify the optimum input parameters in WEDM of DIN 1.4542 hardening stainless-steel alloy. They considered power, T_{OFF} voltage and servo and number of finish passes, as input parameters and surface roughness and maximum thickness of white layer as output responses. Hassan et al. [30] presented the experimental work

to study the effects of process parameters: pulsed current and pulse-on duration on surface texture of AISI 4140 steel in WEDM process. They found from their study that pulse-on duration is most influential factor than pulsed current to defining the WEDM surface texture.

The P91 steel is extensively used for energy-based industries such as reactor components due to its excellent mechanical properties like high creep strength and thermal conductivity, low thermal expansion, good corrosion resistance, [37, 38] etc. Bhattacharya et al. [32] studied the corrosion behavior of P91 steel material in WEDM process. They stated that WEDMed surfaces have fine passivation than the diamond polished surface.

AISI D3 die-steel possess high resistance to wear and exhibits resistance to heavy pressure which extensively used for applications like blanking, stamping and cold forming dies and punches for long runs and lamination dies [39]. Muthukumar et al. [39] conducted experiments to study the influences of input factors such as T_{ON} , T_{OFF} , gap voltage, wire feed on MRR, R_a and kerf width in WEDM of AISI D3 die-steel. They found improved quality responses through systematic analysis of WEDMed die steels.

SKD11 steel is a high-carbon, high-chromium alloy tool steel which used to make dies, precision gauges, spindle, jigs and fixtures, [40] etc. Zhang et al. [40] had made research analysis to seek optimal output responses: MRR and 3D surface quality (S_q) by controlling the input parameters in WEDM of SKD11 steel. Investigators had been improved the performance of WEDM process by systematic analysis and optimization.

One can found more reported articles on machining of stainless steels and alloys in WEDM from the literature. Here, some of the published papers have been presented in **Table 2**.

3. Conclusions

Followings are the conclusions drawn from the present study of machining of stainless steel and its alloys using EDM and WEDM:

1. A historical review of steel and its alloys have been discussed.
2. Stainless steels and alloys are the widely used industrial material for various advanced applications like aerospace, automobile, surgical, mold, tool and die industries
3. The importance of machining of stainless steels and alloys have been discussed
4. NTM processes are extensively used for producing complicated shapes or features on these materials
5. EDM and WEDM are the important NTM methods which highly used by metal cutting
6. Selection of input process parameters is very important for both EDM and WEDM techniques
7. The effects of input parameters on output performance characteristics of EDMed or WEDMed parts needs to be understand properly

8. Systematic analysis and proper understanding of these methods are important to make effective use of EDM and WEDM processes
9. More extensive research needs to be conducted on stainless steel and alloys in EDM and WEDM methods to enhance the performance of machining

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Conflict of interest

The author declaring no conflict of interest.

Notes/thanks/other declarations

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