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ORIGINAL PAPER

Investigation of wire-cut EDM process parameters on Nimonic 90 made by wire arc additive manufacturing process

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Abstract
Incurrent times wire arc additive manufacturing is becoming popular and alternate to conventional machining because of its eco-friendly as wastages. Wire arc additive manufacturing (WAAM) develops the parts by depositing wire material one layer above other because it is based on old technology i.e., welding. It even has ability to generate complex parts. As WAAM requires post processing to obtain the better surface and accuracy of dimensions. To study about the post processing of WAAM specimen, in this work Wire cut EDM is used, which can machine complicated shapes with high accuracy for any conducting material without taking into account the hardness of the material. Selection of input parameters is the key for better material removal and surface finish in Wire EDM.In this study Pulse on time, Wire tension, Servo Voltage withthree levelswereconsidered as input parameter and Material removal, Surface roughness are considered as output responses. Response surface Methodology is used for designing the experiment. It is observed that wire tension plays vital role in material removal and surface finish, pulse on time is important in material removal but not in surface finish. Servo voltage predominant for surface roughness but less influenced on material removal rate.

Keywords WAAM · Subtractive manufacturing · Wire EDM · Nimonic 90 · RSM · Wire tension · Servo voltage · Pulse on time · MRR · Surface roughness

1 Introduction

Manufacturing techniques have seen major industrial advancements over the past 50 years, despite many inefficiencies such as the inability to process particular materials, create complicated shapes, and manufacture in huge quantities. In subtractive manufacturing, a lot of waste is produced [1]. Architects and designers have used 3D printing extensively to make aesthetically beautiful and useful prototypes in the past due to its speedy and economical prototyping capabilities[2]. However, until recently, 3D printing wasn't being used effectively in a number of businesses. Many plastic parts, including the vacuum cleaner's body and clothing, were initially produced using additive manufacturing. The production environment will, however, be dramatically altered by the use of metals or ceramics in additive manufacturing in the aerospace and medical sectors. By predominantly using metal and ceramic in the form of fused powders, AM varies from traditional manufacturing or subtractive manufacturing, because there aren't enough machine makers and quantifying surface texture in additive manufacturing is more difficult than it is in traditional machining, WAAM hasn't fully industrialized [3]. The demand for high quality production and complicated metal structures has fueled the growth of additive manufacturing over the past few decades. One AM method that employs metallic materials in its fabrication is called wire arc additive manufacturing [4]. When compared to conventional manufacturing, this technology's utilization of industrial robots and welding equipment improves performance by 40–60% and speeds up production by 15–20%, depending on the size of the product [5]. In AM, Materials are efficiently joined layer by layer, and net shapes are created with little expense and geometry resolution [6]. Arc-based technology, used by WAAM, has increased productivity, high energy efficiency, and lower material costs. Compared to traditional welding, where the buy-to-fly ratio

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is 4.9 and includes machining finish, WAAM saves material [7]. Wire is used as a filler in the Direct Energy Deposition form of additive manufacturingor WAAM, in which an electric arc serves as the heat source to melt the wire. One arc process that works best in WAAM is cold metal transfer; in this process, consistent, well-controlled current waves are present, along with filler feed. This results in the weld bead being deposited with fewer protrusion [8]. WAAM has capacity to produce goods with higher quality, robust structures, and favorable mechanical properties has helped it gain appeal [9]. Although WAAM is a new technique within AM, there are various challenges that must be overcome, such as: (i) The major loss in WAAM is tolerance, which is produced by residual stress and input heat distortion. (ii) Accuracy in dimensions and component resolution. (iii) The surface quality of WAAM component manufacturers is low [10]. To achieve precise dimensional accuracy, subtractive manufacturing and WAAM are coupled. In the course of post-processing, subtractive manufacturing should only be used after WAAM [11]. Kindermann et al. studied about dissolution of Nb in eutectic phase around the interlayer regions in CMT WAAM of processing parameters [12]. Effect of IN 718 alloy cold rolled with isothermally aging for 8 h at 800 °C is investigated by Mei et al. [13]. Jung Hyun park et al.has investigated the development of 9% nickel steel with 625 alloy of super TIG welding, it has been observed that compared to conventional fluxed cored arc welding, Super TIG welding exhibited high tensile strength, Impact toughness, hot cracking resistance which are due to low non-metal inclusion in metal [14]. Nickel-based super alloys are used in additive manufacturing which are second to titanium alloy in popularity. Due to its favourable mechanical qualities and corrosion resistance, particularly at high temperatures, nickel super alloys are used in the aerospace, energy, and petrochemical industries [15]. One of the nickel-based super alloys, Nimonic 80, is resistant to heat, oxidation, and corrosion, especially at high temperatures, making it valuable for gas turbine engine parts, the space industry, and nuclear reactors [16, 17]. Nimonic 90 is a nickel-based super alloy. It has excellent corrosion resistance, high thermal stability, and unique properties like strong affinity to heat, low thermal conductivity, and low diffusivity, which makes it challenging to build via subtractive manufacturing [17]. When nickel alloys are machined using conventional techniques, a built-up layer forms on the cutting tool face, the surface integrity is sub-par, and there are numerous microcracks, including surface ripping, material pull-out/cracking, and drag [18]. This type of hard materials can be machined by using chemical reactions, melting and evaporation with electrical energy known as non- traditional machining, WEDM is one among non-traditional machining which can machine any material that is conductive in nature without considering its hardness and brittleness. In WEDM energy is discharged as discrete, which occurs at between wire electrode and workpiece through dielectric fluid. The energy discharged produces a temperature of around 20,000 °C between electrodes in very less microseconds [19]. To get a superior surface finish, tool wear and vibration during machining must be controlled. This is because direct contact between the wire electrode and the workpiece occurs during WEDM, which causes mechanical stress. It is never easy to attain acceptable surface roughness and a higher rate of material removal because better material cutting and better surface finish are always at odds with one another [20]. In order to provide insulation and ionisation between the workpiece and the wire electrode, the de-ionized water functions as a dielectric medium. A spark caused by electricity generates a significant quantity of heat, which is cooled by a dielectric medium, which also removes the eroded material from the surface of the material [21]. For better material removal rate, surface roughness, and kerf width, many researchers have tried to optimise the process parameters, such as pulse on time, pulse off time, wire tension, open servo voltage, and flushing pressure. However, experimental evidence from Manna et al. suggests that wire tension and wire feed have good effects on surface roughness while open servo voltage, pulse on time have significant effects on material removal rate [22].

Although WAAM has gained industrial acceptance by producing final parts in accordance with the specified designs, a secondary subtractive operation is still required. In order to produce the specimen's surface polish and to first detach the WAAM specimen from the substrate, subtractive manufacturing is required. It has been noted that while many academics have produced extensive research on the WAAM method utilising a variety of materials, very few papers have focused on Nimonic 90 which is one of the nickel-based super alloys that is widely utilised in various applications due to its resistance to oxidation at high temperatures as well as its resistance to corrosion. Few researchers have integrated a few additive and subtractive manufacturing processes, however WAAM and WEDM have not yet been integrated. Therefore, a part is created in this article using Nimonic 90 wire in WAAM, and then WEDM is utilised to analyse how parameters affect the part's machining. Servo voltage, pulse on time, and wire tension were selected as the input parameters in accordance with previous studies and the objective of this investigation, which is to obtain a high material removal rate and minimal surface finish. By using Design of Experimentsthree levels of WEDM input parametersservo voltage, wire tension, and pulse on time are designed using the RSM technique.

Table 1 Composition Nimonic 90

Element	Content (%)
Iron (Fe)	58.5
Chromium (Cr)	19.5
Cobalt (Co)	18
Titanium (Ti)	2.5
Aluminium (Al)	1.5

Table 2 Technical specification of maxi-cut eWEDM machine

1	Max. table size	440 × 650 mm
2	Max. height	200 mm
3	Max. weight	300Kg
4	Controlled axes	X &Y, U&V
5	Wire range in dia.	0.25 mm (std) & 0.15–0.3 mm (Opt)
6	Memory	1000 blocks with battery backup
7	Tank capacity	250 L
8	Generator	ELPULS 20e
9	Load	07 Kilo VA
10	Average consumption of power	3.5 to 05 Kilo VA
11	Input power supply	3Phase, AC 415 V, 50 kHz

2 Experimental set-up

2.1 Material and machine

Nimonic 90 wire material of 1.2 mm diameter whose chemical composition is shown in Table 1. The Schematic diagram of WAAM machine is shown in Fig. 1. Teach pendent is the technique used in this study.

Welding torch can moves about X axis,Y axis and Z axis. The shielding gas used in this study is Argon. MIG welding technology. A part of 12 cm×12 cm×6 cm of nimonic 90 is developed on Stainless Steel substrate of 10 mm thick.

Wire electric discharge machine of Maxi-cut eis used to perform the experimentation. The technical details of the machine are shown in Table 2 and it is shown in Fig. 2.

Copper, Brass, Zinc coated brass are wire electrodes of diameters ranging from 0.05 to 0.25 mm are generally used in WEDM. The eroded material is flushed by passing dielectric fluids like De-ionized water, Kerosene. Dielectric fluid helps in reducing the short circuit between workpiece and wire [23]. De-ionized water as dielectric medium, Zinc coated brass wire of 0.25 mm is used for cutting of the specimen because zinc coating gives better tensile strength and zinc vaporizes quickly and enhances gap between wire electrode and specimen which intern leads to flushing of eroded material, brass inside will get better cooling and avoids wire breakage.Range of parameters are shown in Table 3 [24]. The input parameters and its level are shown in Table 4.

Experiments were designed by using RSM Central Composite design.Square profile of 5 mm is designed in CAD software and is imported into NCP file and loaded to Maxi E Cut WEDM machine. Material removal rate and Surface roughness were taken as output responses. Material removal rate is calculated using the formula [25].

$$\text{MRR} = \frac{Volume\ of\ material\ removed\ \left(mm^3\right)}{Time\ takem\ for\ complete\ cutting\ of\ one\ specimen\ (min)} \quad (1)$$

- Volume removed = Perimeter of specimen × Dia. of wire× thickness of work-piece.
- Perimeter = 4 × each side size (5 mm)
- Diameter of wire = 0.25 mm.
- Thickness of specimen = 5 mm.
- Time taken to cut each specimen.

Fig. 1 WAAM machine

Fig. 2 Maxi-cut e WEDM machine

Table 3 Maxi-cut eWire EDM process parameters & its range

S. No	Process parameter	Range
1	Pulse on time	0–131 (µs)
2	Pulse off time	0–63 (µs)
3	Wire tension	0–15 (N)
4	Servo voltage	0–99 (V)
5	Water pressure	0–15 (kg/sq cm)
6	Wire feed rate	0–15 (m/min)
7	Peak current	Upto 230 (A)

2.2 Calculation of MRR

$$\text{MRR} = \frac{4 \times 5 \times 0.25 \times 5}{7} == 6.25(\text{mm}^3/\text{min}).$$

By using above formula, we can able to calculate the MRR of all the specimens and surface roughness are calculated by using Taylor surf device. The responses are tabulated for all the 20 experiments in Table 5.

3 Results and discussion

3.1 Variation of responses with input parameters

The variations in responses with input parameters are studied using main plots. Main plots are drawn using Minitab 2021software.

3.2 Effects of Input parameters on MRR

Main effect Plot of MRR with Pulse on time, Servo voltage and Wire tension are shown in Fig. 3. With increase in wire tension, Pulse on time there is increase in material removal rate and with increase in servo voltage MRR increase initially then material cutting rate decreases. During initial increase of servo voltage MRR increases, as there is increase in sparks between the electrodes which heats and evaporates the material. Whereas when voltage increases there is increase in current but less amount of heat gets transmit to workpiece since gap increases between electrode, which leads to decrease in MRR [26]. As Wire tension increases there is decrease in vibrations and makes wire electrode straight which leads to increase in cutting of material from work piece[27]. It is observed that with increase in pulse-on

Table 4 Input parameters with its levels

Parameters	Unit	Levels		
		– 1	0	1
Pulse-on time	µs	7	8	9
Servo voltage	Volts	2	3	4
Wire tension	N	1000	1150	1300

Table 5 Experimentation responses

S. No	T_{on} (µs)	SV (V)	WT (N)	MRR (mm^3/min)	SR (µm)
1	80	50	10	3.570	3.257
2	110	50	12	6.950	3.658
3	80	80	12	3.650	3.106
4	95	65	11	5.950	3.298
5	95	65	11	6.100	3.997
6	110	80	10	6.512	3.842
7	110	80	12	7.210	3.675
8	95	65	11	6.085	3.705
9	80	50	12	5.850	2.890
10	80	80	10	3.256	3.756
11	95	65	11	6.085	3.551
12	110	50	10	6.521	**4.499**
13	95	80	11	5.750	**2.988**
14	110	65	11	6.480	3.992
15	95	65	11	6.224	3.530
16	80	65	11	4.125	3.306
17	95	65	10	5.325	3.885
18	95	50	11	5.810	3.499
19	95	65	11	5.980	3.516
20	95	65	12	6.350	3.257

there is increase in cutting of material i.e., material removal. This is due to increase in length of pulse will increase in energy discharged, melting of material and flushing of material [28].

3.3 Effect of input parameters on Ra

Main effect Plot of Surface roughness with Pulse on time, Servo voltage and Wire tension are depict in Fig. 4. From figure it is observed that with increase in Pulse on time there is increase in Surface roughness whereas with increase in wire tension, Servo voltage surface roughness decreases. With increase in servo voltage stability in spark and uniformity in dispersion occurs which leads to improvement in surface finish [29]. When wire tension is low surface roughness is more and less for high values of wire tension, this due to fact thatas wire tension increases there is reduction in deflection of wire which is due to reactional force to the sparks developed and water pressure. This reduction in deflection of wire from path, leads to proper machining and produces better surface finish [30]. During pulse time, bridge of spark is developed between the electrodes, which generate current. As pulse time increases sparks becomes longer which leads to formation to formation of deeper, boarded cuts on surface, thus surface roughness increases [31].

3.4 Contribution of process parameters

Contribution of process parameter for output responses with respect to input parameters are shown by Figs. 5 and 6.

3.5 Analysis of surface topology of WEDM process

After WEDM operations, the scanned electron microscope(SEM) made by Joel 6067 been used to investigate the change insurface properties of work material after WEDM process. It has been examined that large number of micro cracks, crater formation,white layer formation and recast layer formation takes placeon the surface of the work material after WEDM which were confirmedby SEM image. This can be observed that higher Ton results in generation of higher thermal energy, when the temperature reaches above 10,000 °C, which is high enough to melt and evaporate the metal and pressure is being buildup inside the melt,when it reaches its limit, it explode, which can splatter melted material on the surface, produce pockmarks, micro holes and globules, resulting in an irregular surface as can be seen in Fig. 7 [32]. It can also be observed that with the rise in SV, the roughness of the surfacealso increases as it generate more thermal energy in the gap, causing stern cracking of the dielectric to happen more frequently, leading to the formation of a molten pool that is becoming overheated. This molten metal condenses onto gas bubbles since it evaporates [33].

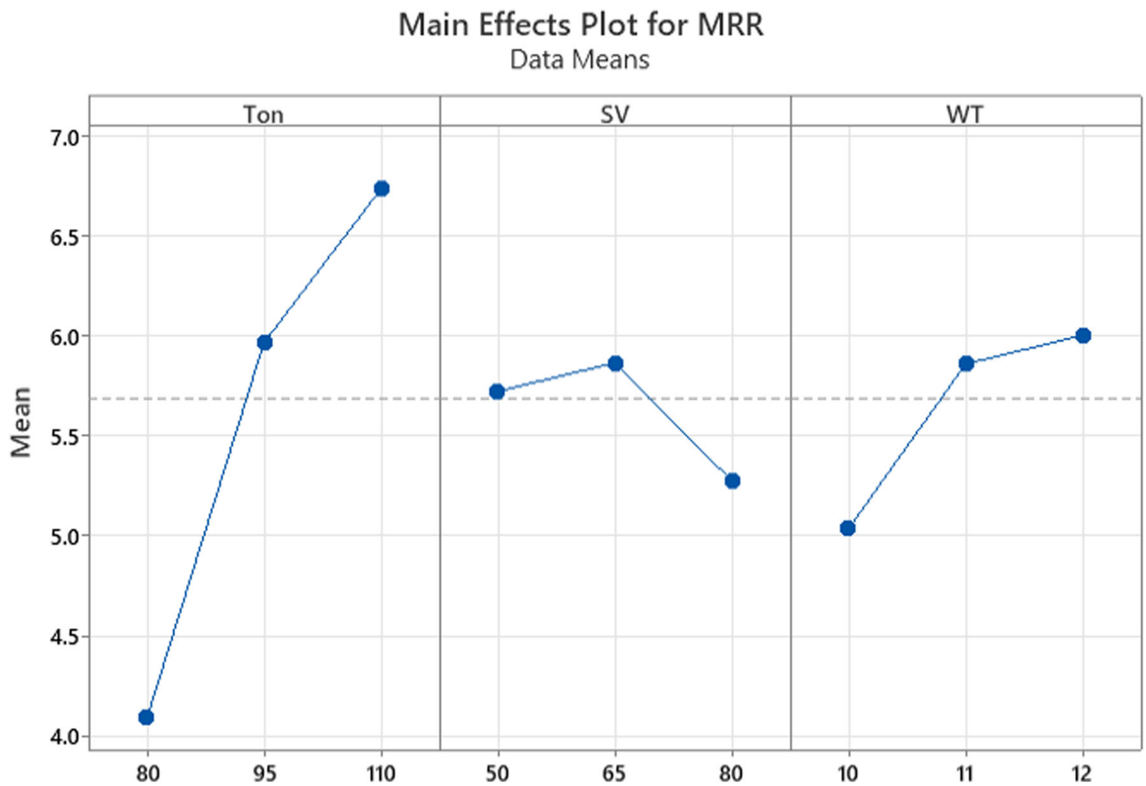


Fig. 3 Main Effect plot for MRR

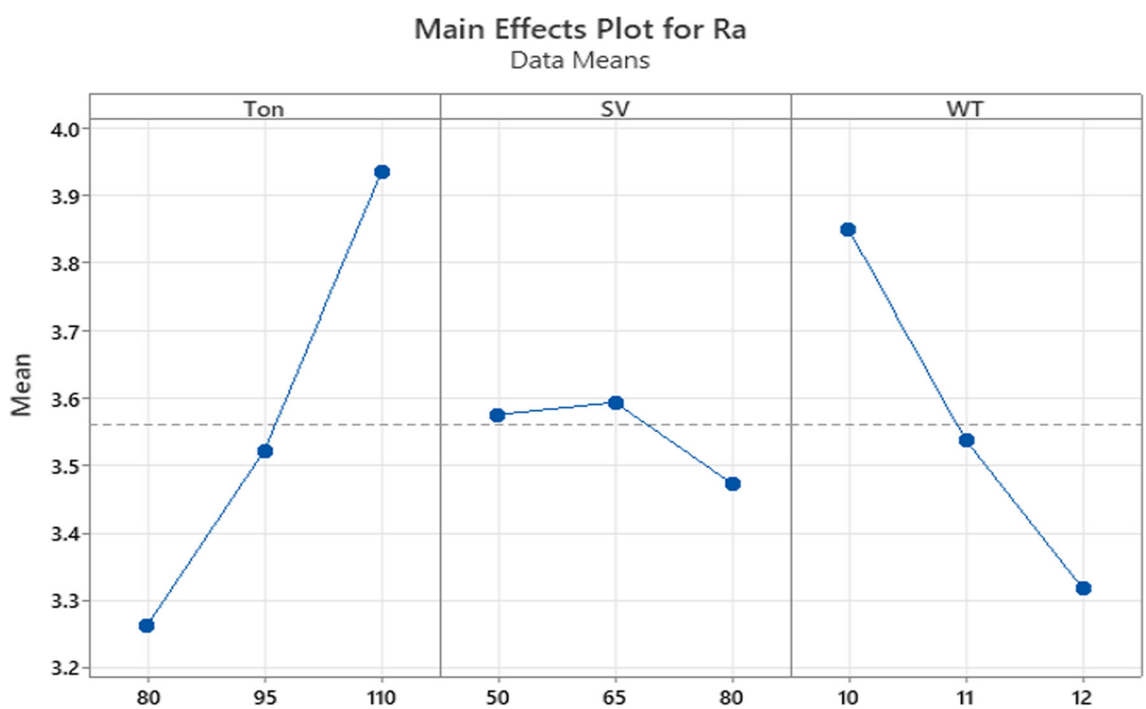


Fig. 4 Main Effect Plot for Ra

Fig. 5 % Contributionof Responses on MRR

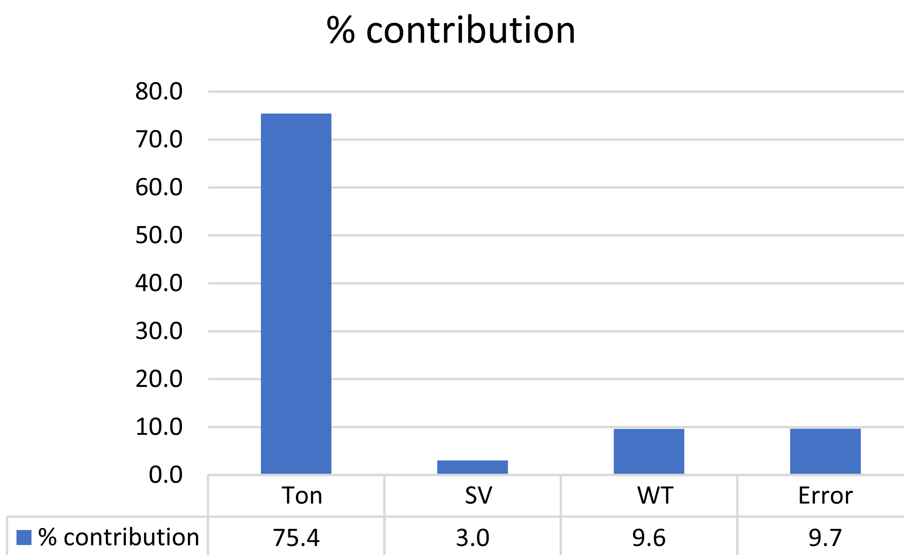
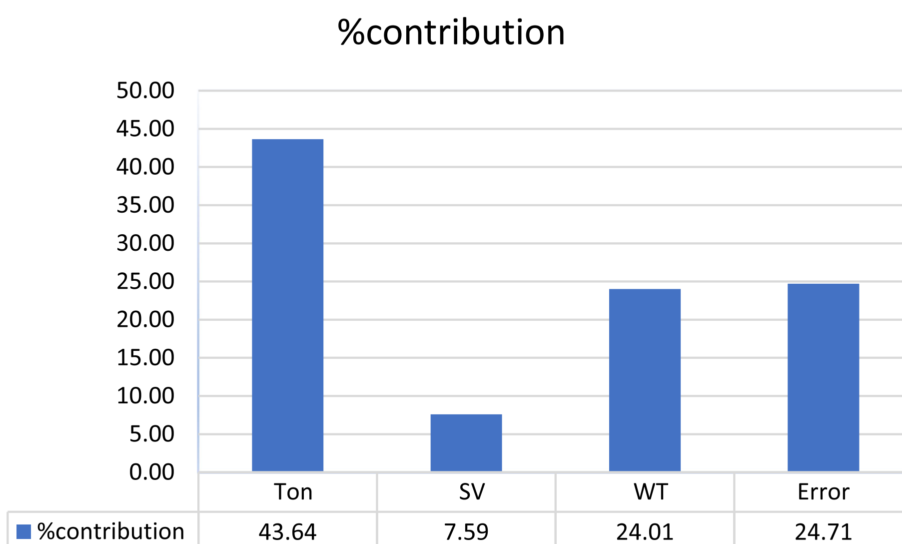


Fig. 6 % Contribution of Responses on Ra



When the charge stops, the gas bubbles shatter, expelling the molten metal from the surface of the Nimonic alloy. Consequently, a big lump of re-solidifiedmass has appeared on the machined surface with big and wide crack. Further size and population of craters were increased extremely and overlapped craters were extended to the complete surfaceas illustrated in SEM micrograph Fig. 8 [34].

4 Conclusion

Nimonic 90 was made in WAAM for experimental purposes, and it was machined using WEDM. For 20 experiments that were designed using RSM, the outcomes are as follows. With varying input parameters, main graphs were created for the output responses.

- It has been found that servo voltage has less of an impact on MRR than do pulse-on time and wire tension. The plot demonstrates that as pulse on time and wire tension increase, MRR also does. This is because an increase in discrete energy with increasing pulse on time melts and evaporates more material, whereas an increase in wire tension results in a stiffer wire and more evenly distributed energy, leading to an increase in MRR.
- MRR first rises as servo voltage rises, but falls as voltage rises more. There is a tiny space between the electrodes when the servo voltage rises, and this heat-generating gap causes additional material to melt and evaporate. MRR, however, diminishes when servo voltage increases the space between the wire electrode and workpiece, which in turn reduces the heat generated between them.
- Surface roughness is seen on plots to grow with pulse on time but decrease with servo voltage and wire tension.

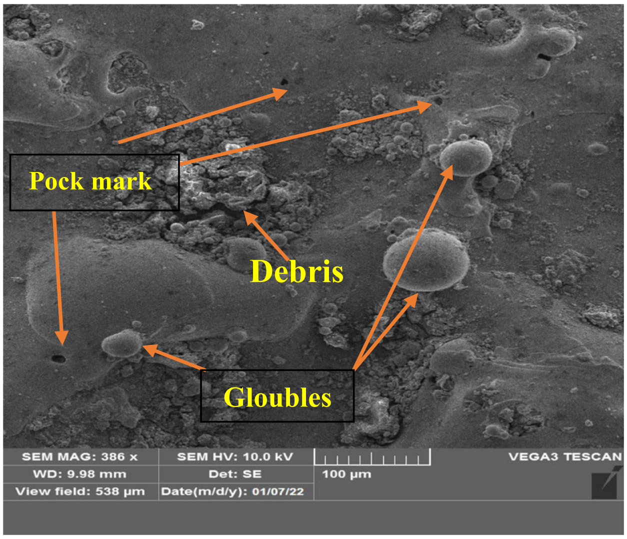


Fig. 7 Sem analysis of Experiment 12 ($T_{on=}$110, SV = 50 V, WT = 10 N)

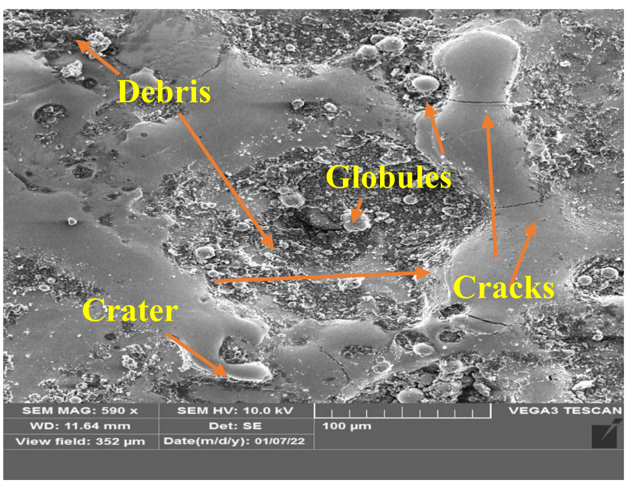


Fig. 8 Sem analysis of Experiment 13 ($T_{on=}$95, SV = 80 V, WT = 11 N)

The depth and size of the craters that are produced on the workpiece's surface grow when the pulse on is increased.

- As wire tension increases, the deflections of the wire diminish, which reduces uneven material removal. Surface roughness will be reduced as servo voltage increases because heat is reduced and less material is removed as a result.
- Microcracks, globules, and craters generated on the specimen's surface are visible in the SEM scans. Microcracks emerge as a result of residual strains on the specimen brought on by thermal stresses during energy discharge and dielectric media cleansing pressure.
- The surface tension of the degraded particles causes globules to develop. Because of the abrupt cooling caused by the dielectric medium, craters are created when material resolidifies on the surface of the substance.

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