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Investigation of Surface Roughness of WAAM Specimen Machined in Wire-Cut EDM

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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 surface finish in Wire EDM. Mechanical properties are used for testing of specimen are Tensile test, Compression test, and Izod test.

In this study Pulse on time, Wire tension, Servo Voltage with three levels were considered 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 surface finish, pulse on time is important in material removal but not in surface finish. Servo voltage predominant for surface roughness.

Keywords: WAAM · Subtractive manufacturing · Wire EDM · Nimonic 90 · Response Surface Methodology · Wire tension · Servo voltage · Surface roughness.

I. INTRODUCTION

A. 3D Printing

3D printing is the construction of a three-dimensional object from a CAD model or a digital 3D model. It can be done in a variety of processes in which material is deposited, joined or solidified under computer control, with material being added together (liquids or powder grains being fused), typically layer by layer.

B. Wire Arc Addative Manufacturing (WAAM)

WAAM has significant potential for cost and lead time reduction for medium-to-large scale engineering components of medium complexity. Careful design for WAAM can enable some topological optimization and careful selection of wire feedstock can make added material optimization and multi-material components possible. If Additive Manufacturing is combined with a machining platform, it becomes possible to create some otherwise impossible shapes. The surface finish (waviness) of WAAM usually means the part must be finish-machined to achieve geometrical or surface finish requirements. However, the envelope of material to be removed can be as little as 1mm; this does not increase with component size, so material efficiency actually increases as parts get larger. WAAM is not a net-shape or fully automated process at this time; until fully capable commercial AMCAD/CAM software becomes available, the part model must be interpreted and the manufacturing process manually prepared, so some operator skill is required for successful part build.

C. Working Principle of WAAM

Wire arc additive manufacturing (WAAM) is a fusion manufacturing process in which the heat energy of an electric arc is employed for melting the electrodes and depositing material layers for wall formation or for simultaneously cladding two materials in order to form a composite structure. WAAM performs layer by layer deposition of weld beads, resulting in a metallic wall with a minimum width of 1–2 mm, followed by build machining to obtain a smooth surface. This resembles cladding in which the successive deposition of the wire feedstock is carried out over a substrate that may be a part of the final build or may be removed by the machining process. The welding technology that can be employed in WAAM is MIG welding. The schematic diagram of WAAM process is shown in Figure 1.1.

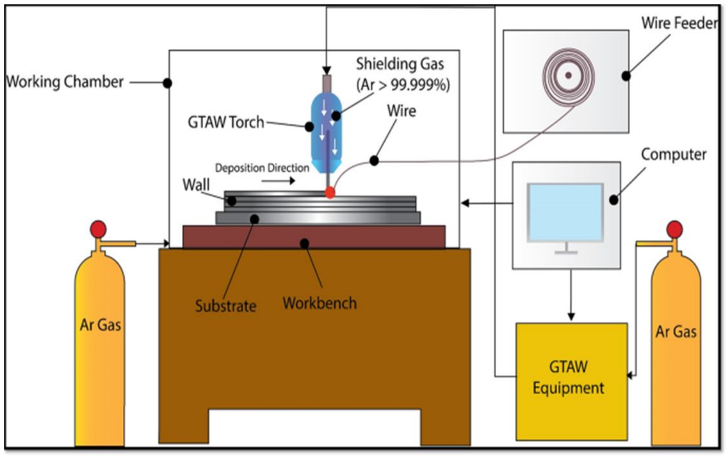

Figure 1.1 Schematic diagram of WAAM

D. *Wire Electrical Discharge Machining (WEDM)*

Wire electrical discharge machining is a high-precision method for cutting nearly any electrically conductive material. A thin, electrically-charged EDM wire held between upper and lower mechanical guides forms one electrode, while the material being cut forms the second electrode. Electrical discharge between the wire and the work piece creates sparks that rapidly cut away material. The deionized water passed between wire and work piece and allows the debris to be flushed away. As the charged wire never makes physical contact with the work piece in WEDM machining, there are no cutting forces involved, making it possible to manufacture extremely small and delicate parts. Parts that require levels of accuracy and intricacy that traditional machining cannot achieve can easily be produced via wire EDM.

E. *Working Principle of WEDM*

The basic mechanism of material removal in Wire-cut EDM is same as that of Die-sink EDM and instead of electrode, a slowly moving wire is used which travels along a prescribed path and removes material from the work piece. A vertically oriented wire is fed into the work piece continuously travelling from a spool to take up spool, so that it continuously renewed, since it will get worn outduring the process. The material is removed by a series of discrete discharges between the wire electrode and the work piece in the presence of dielectric fluid, which creates a path for each discharge as the fluid becomes ionized in the gap. The area where discharge takes place is heated to extremely high temperature, sothat the surface is melted and removed. The removed particles are flushed away by the flowing dielectric fluids. The schematic diagram of WEDM process is shown in Figure 1.2.

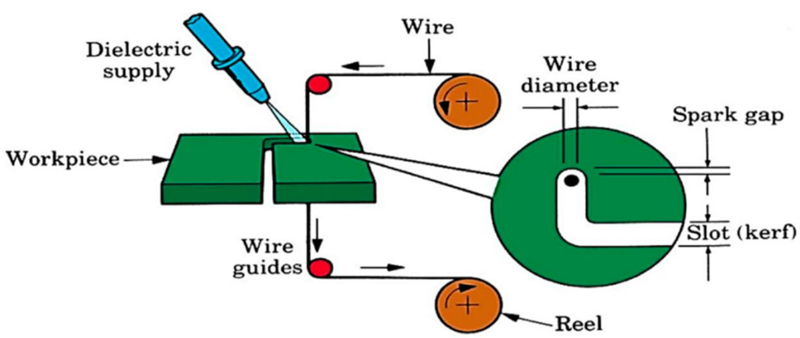

Figure 1.2 Schematic diagram of WEDM

The wire is held between upper and lower guides. The guides move in the (X-Y) plane controlled by a CNC, the upper guide can also move independently in the (Z-U-V) axis, giving rise to the ability to cut tapered and transitioning shapes and can control axes movements. This gives the Wire-Cut EDM the abilityto be programmed to cut very intricate and delicate shapes. Wire EDM has no added residual stress as there is no cutting forces involved during machining. WEDM process is used for cutting intricate shapes, to make punches, dies and tools from any conductive material. The wire does not touch the work piece, so there is no physical pressure imparted on the work piece compared to grinding wheels and milling cutters.

F. Wire as Electrode

Characteristic of wire electrode is one of the major factors affecting the performance of Wire EDM i.e., the cutting performance and the wear of the WEDM process depends upon a combination of the electrical, mechanical, physical and geometrical properties of the wire electrode. In this project work both zinc coated brass wire and LN2 cooled Zinc Coated brass wire are used. The electrode without and without treatment is maintained a diameter 0.25mm. Zinc coated brass wire has lot of advantages compared to plain brass wire.

The advantages are:

1) In zinc-coated brass wire the brass wire is electroplated with high purity zinc.
2) The productivity will increase with coating.
3) The discharge of energy becomes stable and free of irregularities.
4) The surface roughness will be improved.
5) Zinc coated wire have tensile strength of 883MPa which is greater than brass wire and hence the breakage of wire is reduced.

II. LITERATURE REVIEW

Andrei E Balanovskiy (2017) "A review of the wire arc additive manufacturing of metals: properties, defects and quality improvement. Journal of Manufacturing Effect of the Wire Arc Additive Manufacturing Process" has investigated the study that the parameters determined during the experiments can be used for the deposition of real parts prototypes. Further adjustment of the parameters will be required during the actual deposition process to achieve better results. Anton A. Kulikov (2018) "Effect of the Wire Arc Additive Manufacturing Process Parameters on the Quality of Steel Components" has investigated the study on the influence of process parameters on the quality of steel components. During the course of the experiment, the relationship between the deposition speed and the geometry of the resulting bead was obtained. The most optimal torch travel speed for the deposition of steel parts using a 0.8 mm wire is 0.003 m/sec at a welding current of 100A. This speed allows achieving the best bead formation with the least distortion. Eschelbacher, S (2020) "Hardness and Orthogonal Cutting Analyses of a Wire and Arc Additive manufactured (WAAM) sample" has examined that both structure-borne noise and force signals (cutting/passive force) during orthogonal machining, different defects were detected. In addition, the combined physical observation of structure-born sound and force offers the possibility to distinguish between individual types of defects. Maider Arana (2021) "Influence of deposition strategy and heat treatment on mechanical properties and microstructure of 2319 aluminium WAAM" has examined, that components of high mechanical properties were obtained, greater than the bibliography, with low anisotropy for particular WAAM manufacturing conditions of 2319 aluminium alloy. The influence of deposition geometry, deposition strategy and heat treatment has been investigated. Aging heat treatment with 190 °C temperature and 26 hrs is recommended to guarantee low anisotropy and therefore, this aging thermal treatment in combination with deposition strategies causing equiaxed grains must be employed in order to ensure the best balance of mechanical properties and isotropy. Tiago A. Rodrigues (2021) "Steel-copper functionally graded material produced by twin-wire and arc additive manufacturing (T-WAAM)" has investigated the study on the fabrication of an HSLA-steel to copper–aluminum alloy functionally graded material using the twin wire and arc additive manufacturing (T-WAAM) technique. The FGM revealed no defects and had excellent high strength and ductility in the interface. Ayan Pramanick et. al (2016) "Optimization of wire electrical discharge machining parameters for cutting electrically conductive boron carbide" has examined that Pure boron carbide (B_4C) was consolidated using spark plasma sintering (SPS) at 2050°C with a dwell of 10 min under 50 MPa uniaxial pressure in Argon atmosphere. The design of experiment (DOE) was arranged by L32 orthogonal array (OA) between the machining input parametersnamely pulse on-time, pulse off-time, pulse peak current, dielectric fluid pressureand servo feed rate and the output responses like machining speed and surface roughness (Ra). Experimental observations were utilized to formulate the first- order regression models to predict responses of WEDM. The optimized input parameters were 27 µs pulse on time, 48 µs pulse off time 180, A pulse peak current, 7 kg/cm^2 water pressure and 2200 mm/min servo feed rate for the WEDMperformance to produce an optimum machining speed and surface finish. Nilesh Patil G et. al (2016) "Semi-empirical modelling of surfaceroughness in wire electro-discharge machining of ceramic particulate reinforced Al matrix composites" has investigated the study was to develop model for surface finish (Ra) based on machining process parameters, material properties, volume fraction and average ceramic particle size. The process behavior and machined surface morphology is affected by volume fraction, sizeof particulated which also alters the thermal and physical properties. Therefore, itwas decided to include the size of particles and the volume fraction to develop anew model for surface finish. Tamang S K et. al (2016) "Integrated optimization methodology for intelligent machining of Inconel 825 and its shop-floor application" has investigated the machining process aims to produce the components for desired surface quality at minimum machining time and cost.

The development of an integrated optimization methodology used for optimizing the process parametersin machining Inconel 825 aerospace alloy. Turning experiments have been conducted with spindle speed (*N*), feed rate (*f*), and depth of cut (*d*) that are considered as process parameters and the Centre line average value of surface roughness (R_a) as response. Mohinder Pal Garg et. al (2017) "Prediction of optimal conditions for WEDM of Al 6063/ ZrSiO4(p) MMC" has suggested to achieve close dimensional accuracy in WEDM, the output parameter dimensional deviation is an essential response to be controlled during machining. This study investigates the dimensional deviation induced by WEDM of Al 6063/ $ZrSiO_{4(p)}$ Aluminium Metal Matrix Composite (MMC) by using Response Surface Methodology (RSM). Midthur A. Salman Khan (2019) "Machinability study of Nicolay using different wire electrode in Wire-Cut EDM" has explained Non-conventional machining process is the latest technology which can be used to machine any material without considering its hardness. Wire cut EDM is a one among the non-convention machining process which can be used as a specialized machine to manufacture intricate shapes, contours and complex structures. It can even generate 2D and 3D components with great flexibility and accuracy. It can be able to withstand the competitive market and fulfill the today's market demand by producing parts economically.

III. EXPERIMENTATION (WAAM)

The experiment is done using FRONIUS CMT And YASKAWA WAAM machine from Welding Robot Groups which is Computer Numerically Controlled (CNC) machine. And this WAAM machines has both combination of Cold Metal Transfer in welding technology by MIG Welding. The maximum workpiece height that can be fixed is 497 mm. The pictorial view of FRONIUS & YASKAWA WAAM is shown in Figure 3.1.

Figure 3.1 Pictorial image of WAAM

A. WEDM

Computer Numerically Controlled (CNC) machine. It has control in X, Y, Z and also in U, V directions. The maximum workpiece height that can be fixed is 200 mm. The maximum weight that can be withstand by this Machine worktable is 300 kg and de-ionized water is used as a dielectric fluid. It can adopt a standard wire electrode diameter of 0.25 mm ionized water is used as a dielectric fluid. It can adopt a standard wire electrode diameter of 0.25 mm. The required profile to be cutis drawn and converted into NCP file and finally loaded into the CNC Wire EDM machine. The pictorial view of MAXICUT Wire EDM is shown in Figure 3.2.

Figure 3.2 Pictorial image of Wire-EDM

Characteristic of wire electrode is one of the major factors affecting the performance of Wire EDM. That is, the cutting performance and the wear of Wire in WEDM process depends upon a combination of the electrical, mechanical, physical and geometrical properties of the wire electrode.

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In this project work the zinc coated brass wire of diameter 0.25 mm is used for machining. Zinc coated wirehas lot of advantages compared to plain brass wire. The element zinc is added to copper to produce brass EDM wire, which is the most common EDM wire in use today. Brass wires for EDM are typically an alloy between 63/37 (American and European) to 65/35 (Asian), Cu/Zn ratio. Tensile strengths of brass wires range from 54,000-173,000psi, depending upon the composition of the alloy and its temper. Brass wires are usually a shiny brass color. Coated EDM wires are wires that have had a very thin layer (2-3μm) of pure zinc applied to a brass or copper core. Electro-galvanization is the most precise method of application, depositing pure zinc, atom by atom onto the body of the wire, insuring uniform thickness and surface uniformity. Nimonic 90 is a family of austenitic nickel-chromium-based super-alloys. Nimonic 90 alloys are oxidation-corrosion-resistant materials well suited for service in extreme environments subjected to pressure and heat. The Various parameters which have been optimized from the RSM method, we have selected the L20 of RSM which based on the number of parameters which have been used in experimentation. For four parameters and four value in each parameter the L20 is selected. These are input of our experimentation of WEDM machining. The selected set of parameters in 20 levels are given in Table 4.2.

Table 4.2 Output responses

Wire Tension(N)	Pulse ONTime (μs)	Servo Voltage (SV)	Surface Roughness Ra (μm)	
			Brass Wire	Zinc Coated Wire
10	14	35	4.15	3.371
12	18	35	4.65	3.756
12	14	50	3.85	3.293
11	16	42	4	3.659
11	16	42	3.78	3.864
10	18	50	4.02	4.12
12	18	50	3.75	3.745
11	16	42	3.81	3.989
12	14	35	3.82	3.665
10	14	50	4.05	3.96
11	16	42	3.98	3.747
10	18	35	3.75	3.643
11	16	50	3.89	3.35
11	18	42	3.65	3.73
11	16	42	3.81	3.66
11	14	42	3.85	3.675
10	16	42	3.8	3.668
11	16	35	3.83	3.659
11	16	42	3.79	3.653
12	16	42	3.87	3.666

B. Machined Samples

The machined work pieces of Nimonic 90 are shown in the Figure 4.1 and Figure 4.2

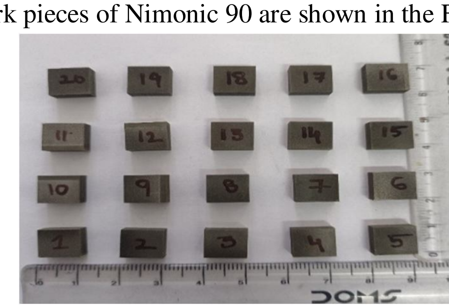


Figure 4.1 Machined samples using Zinc coated Brass wire

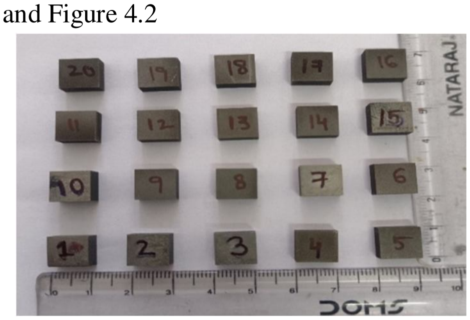


Figure 4.2 Machined samples using Brass wire

C. Effect Of Input Parameters On Surface Roughness (Ra) Brass Wire Cutting

The variation in input parameters on the surface roughness when brass wire is used is shown in Figure 4.5 and Figure 4.6

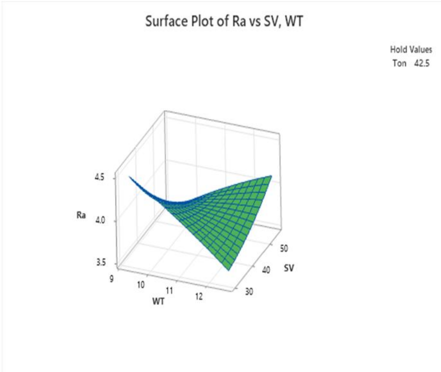


Figure 4.3 Contour Plot of Ra vs WF, SV

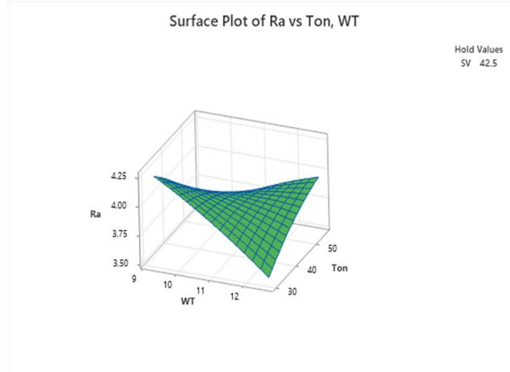


Figure 4.4 Contour Plot of Ra vs WF, SV

The Contour plots of Ra vs WT and SV is shown in Figure 4.3. From the graph it is clear that Surface Roughness gets decreases if the Wire tension and Surface Roughness increases with Servo Voltage increase. The reason behind is high evaporation in material and high sparkvoltage. The Contour plots of Ra vs WT and Ton is shown in Figure 4.4. From the graph it is clear that Surface roughness decreases with increase in Wire Tension and Surface roughness increases with T_{on}. The reason behind is less deflection and high removal of smooth surface

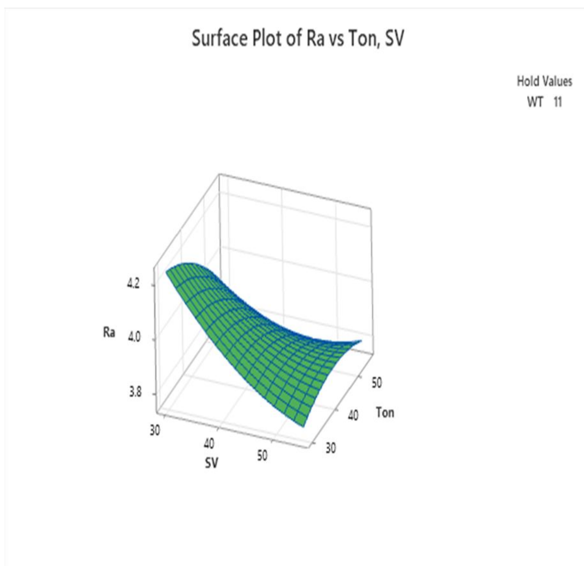


Figure 4.5 Contour Plot of Ra vs SV, Ton

The Contour Plot of Ra vs Ton and SV is shown in Figure 4.5. From the graph it is clear that Surface Roughness gets decreased with Servo Voltage and Surface Roughness slightly increase with Ton increase. The reason behind is high evaporation of material and high discharge per spark which leads to removal of high material.

D. Effect of Input Parameters on Surface Roughness (Ra) By Zinc Coated With Brass Wire Cutting

The effects of input parameter on the response when Nimonic 90 is machined using zinc coated brass wire is shown in Figure 4.6. The Contour plots of $Ra._2$ vs WT and SV is shown in Figure 4.6 (a). From the graph it is clear that Surface Roughness gets decreases if the Wire tension increase and Surface Roughness increase with IP increase. The reason behind is high evaporation in material and high spark voltage. The Contour plots of $Ra._2$ vs Wt and Ton is shown in Figure 4.6 (b). From the graph it is clear that Surface Roughness decreases with increase in Wire Tension and Surface Roughness increase with increase in Pulse off time. The reason behind is less deflection and high removal of smooth surface.

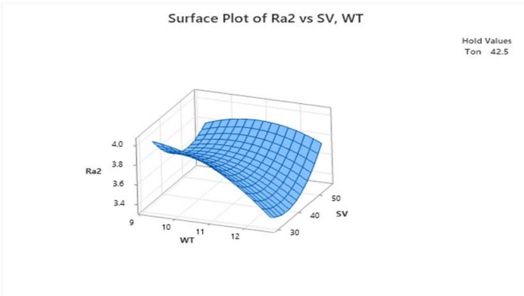


Figure 4.6 Contour Plot of Ra.$_2$ vs SV, WT

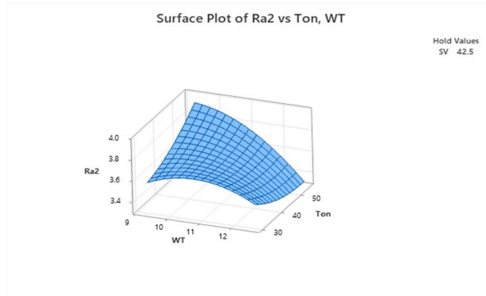


Figure 4.7 Contour Plot of Ra.$_2$ vs WT, Ton

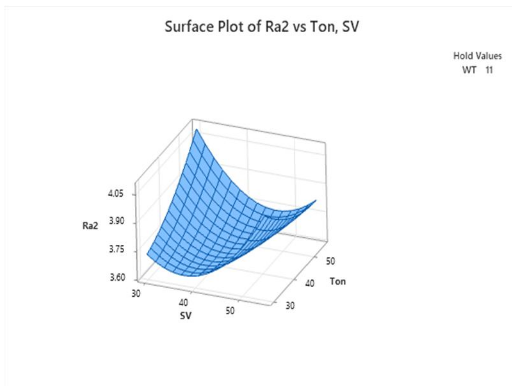
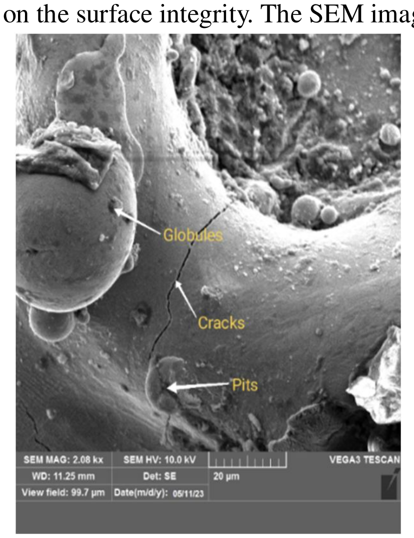


Figure 4.8 Contour Plot of Ra.$_2$ vs SV, Ton

The Contour plots of Ra.$_2$ vs SV and T_{on} is shown in Figure 4.6 (c). From the graph it is clear that Surface Roughness gets decreased if the Serve Voltage increase and Surface Roughness decrease with Pulse off time increase. The reason behind is high evaporation of material and high discharge per spark which leads to removal of high material.

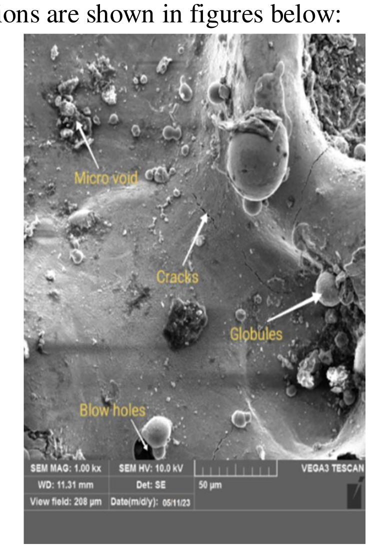
E. SEM Results of WEDM Surface

SEM is used to observe the surface integrity and the surface characteristics of machined work pieces. SEM analysis was carried out on those work pieces in which the input parameters are at low level and high level. This is done so as to analyses what is the variation happening on the surface integrity. The SEM images for various conditions are shown in figures below:



(a)

Figure 4.7 (a) SEM result of Maximum Structure Using Brass wire cut



(b)

Figure 4.7 (b) SEM result of Maximum Structure Using Brass wire cut

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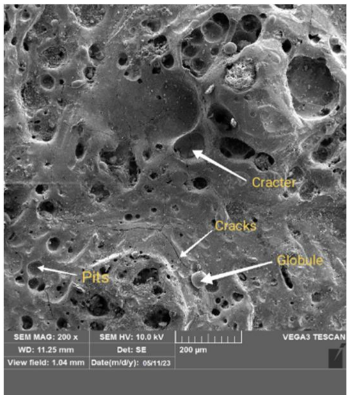
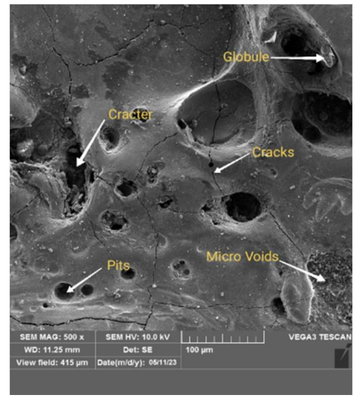


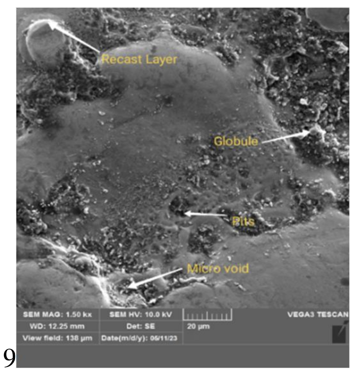
(c)

Figure 4.7 (c) SEM result of Minimum Structure Using Brass wire cut



(d)

Figure 4.7 (d) SEM result of Minimum Structure Using Brass wire cut



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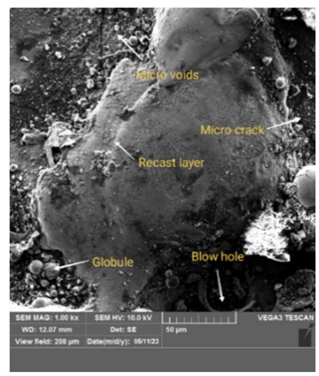
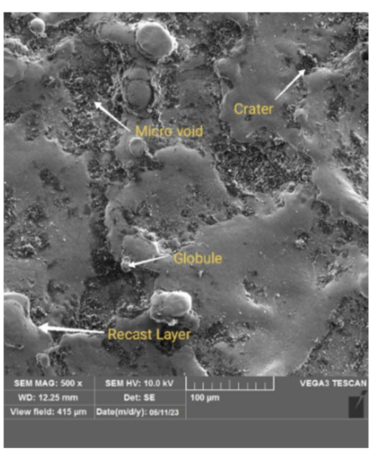
(e)

Figure 4.7 (e) SEM result of Minimum Structure Using zinc coated Brass wire cut



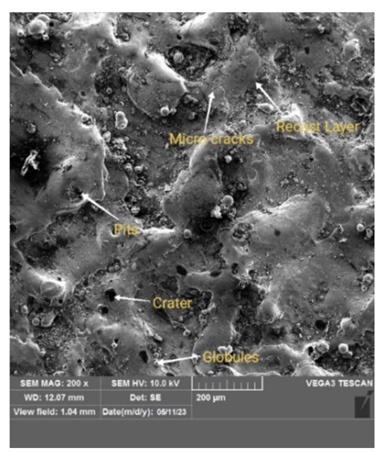
(f)

Figure 4.7 (f) SEM result of Minimum Structure Using zinc coated Brass wire cut



(g)

Figure 4.7 (g) SEM result of Maximum Structure Using Zinc coated Brass wire



(h)

Figure 4.7 (g) SEM result of Maximum Structure Using Zinc coated Brass wire

The Figure 4.7 (a),(b),(c) & (d) shows the SEM images when Nimonic 90 is machined using brass wire. It is observed that there is formation of recast layer, pits, cracks and globules. The crater formed depends upon the impact of pulse discharge energy which decides the erosion rate of the material.

Debris formed when the molten material was not flushed properly by the dielectric fluid. High thermal stress which is developed due to rapid cooling or uneven cooling when exceeding the fracture strength of the material initiates the crack. Material melted by electric sparks and resolidifies on the surface without being ejected nor removed by flushing. Among the two Figures 4.7 (c) & (d), it is observed that Figure 4.7 (d) is having large number of globules of debris, crater and cracks. This is due to high pulse on time which causes large amount of discharge and lead to increase in surface roughness.

Figure 4.7 (a) & (b) is having good surface finish than Figure 4.7 (c) & (d), this is due increase in wire tension. Increase in wire tension decreases the bending of wire and causes homogenous sparking of the energy. Hence less number of pits and micro voids and small globules are formed.

Figure 4.7 (e) & (f) are SEM images for the work pieces which are machined using Distilled die-electric liquid cooled by Brass wire and zinc coated brass and for variation of pulse on time and wire tension respectively. The thermal conductivity of zinc coated treated wire increases which causes heat in inter-electrode gap to dissipate at faster rate when wire is treated using Distilled die-electric liquid cooling. Figure 4.7 (g) & (h) is having big globules and pits than in Figure 4.7 (g) & (h), this is due to the increase in pulse on time. When pulse on time increases the amount of energy 56 discharged increases and causes large amount of material to evaporate. When dielectric fluid is passed to flush off the material some of the materials accumulates and forms big globules.

Figure 4.7 (e) & (f) is having better surface finish than Figure 4.7 (g) & (h). When wire tension is increased the material becomes stiff and when this high tension is cooled with Distilled die-electric liquid, the wire becomes more stiffer and its conductivity also increases. Hence more amount of material is removed and due to homogeneity of spark produced due to high tension causes fewer surfaces which are even observed

IV. CONCLUSION

Nimonic 90 is initially machined using three parameters i.e., Wire Tension, Servo voltage and pulse on time. Among these Servo voltage and pulse on time pays prominent role in wire breakage. So, these are kept at medium level for further conduction of experiments using Zinc coated wire and Brass wire and cooled with Distilled die-electric liquid. Input parameters selected for the experiments are wire tension, wire feed and pulse on time and experiments were designed by using RSM.

1) Pulse on time and wire tension plays prominent role in machining of Nimonic 90.
2) Surface roughness increases with increase in pulse on time but decreases with increase in wire tension.
3) Surface roughness decreases, when the zinc coated brass wire is cooled using Distilled die-electric liquid.
4) To obtain high Surface Roughness wire tension is high, Pulse on time and wire feed is kept medium.
5) Large number of craters, pits and recast layer are formed when pulse on time is increased.
6) Increase in wire tension reduces the formation of recast layers.
7) With Distilled die-electric liquid cooling of Zinc coated brass wire the machined surface obtained have a smaller number of voids, pits and cracks.

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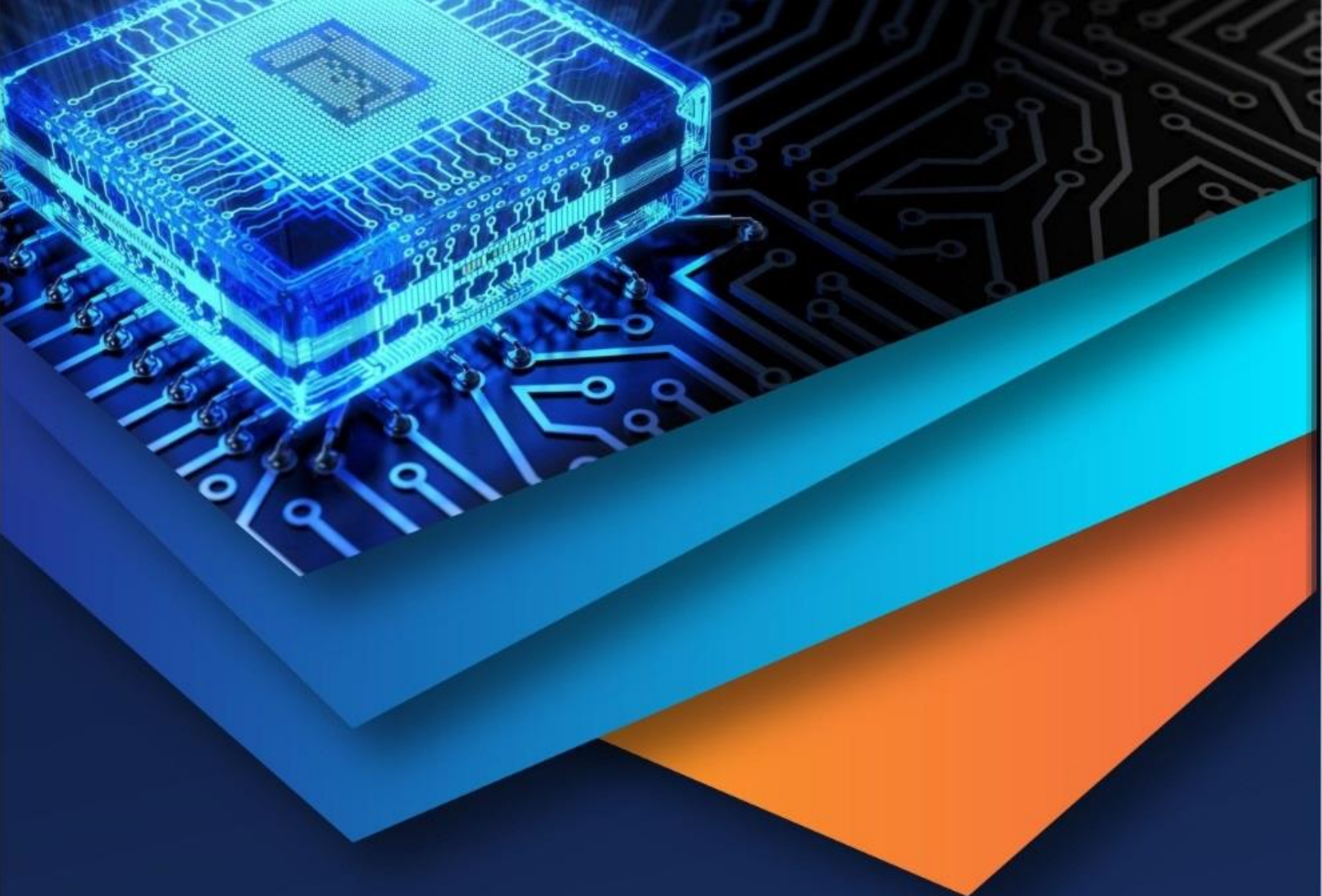

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ISRA JIF IMPACT FACTOR: 7.129

SJIFactor TOGETHER WE REACH THE GOAL IMPACT FACTOR: 7.429

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