KAUNAS UNIVERSITY OF TECHNOLOGY

FACULTY OF MECHANICAL ENGINEERING AND DESIGN

Laurynas Turkas

EXPERIMENTAL AND STATISTICAL INVESTIGATION OF WIRE ELECTRICAL DISCHARGE MACHINING PROCESS

Master’s Degree Final project

Supervisor
Assoc. Prof. Dr. P. Krasauskas

KAUNAS, 2016

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Industrial Engineering and Management (621H77003)

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KAUNAS, 2016

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Industrial Engineering and Management 621H77003

(Title of study programme, code)

EXPERIMENTAL AND STATISTICAL INVESTIGATION OF WIRE ELECTRICAL DISCHARGE MACHINING PROCESS

DECLARATION OF ACADEMIC INTEGRITY

____ ________________ 20 _____

Kaunas

I confirm that the final project of mine, **Laurynas Turkas**, on the subject “Experimental and Statistical Investigation of Wire Electrical Discharge Machining Process” is written completely by myself; all the provided data and research results are correct and have been obtained honestly. None of the parts of this thesis have been plagiarized from any printed, Internet-based or otherwise recorded sources; all direct and indirect quotations from external resources are indicated in the list of references. No monetary funds (unless required by law) have been paid to anyone for any contribution to this thesis.

I fully and completely understand that any discovery of any facts of dishonesty inevitably results in me incurring a penalty under procedure effective at Kaunas University of Technology.

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KAUNAS UNIVERSITY OF TECHNOLOGY

FACULTY OF MECHANICAL ENGINEERING AND DESIGN

Approved:
Head of
Production Engineering
Department

____
(Signature, date)

Kazimieras Juzėnas
(Name, Surname)

MASTER STUDIES FINAL PROJECT TASK ASSIGNMENT

Study programme Industrial Engineering and Management

The final project of Master studies to gain the master qualification degree, is research or applied type project, for completion and defence of which 30 credits are assigned. The final project of the student must demonstrate the deepened and enlarged knowledge acquired in the main studies, also gained skills to formulate and solve an actual problem having limited and (or) contradictory information, independently conduct scientific or applied analysis and properly interpret data. By completing and defending the final project Master studies student must demonstrate the creativity, ability to apply fundamental knowledge, understanding of social and commercial environment, Legal Acts and financial possibilities, show the information search skills, ability to carry out the qualified analysis, use numerical methods, applied software, common information technologies and correct language, ability to formulate proper conclusions.

1. Title of the Project

“Experimental and Statistical Investigation of Wire Electrical Discharge Machining Process”

Approved by the Dean Order No.V25-11-7, 3 May 2016

2. Aim of the project

To investigate experimentically and statistically titanium alloy‘s GR-5 surface roughness depending on wire EDM process parameters.

3. Structure of the project

This project consists of five parts: introduction, theoretical part, literature overview, experimental part and analysis part.

4. Requirements and conditions

Literature overview; Workpieces cutting using wire EDM; Surface roughness mesurement using Mitutoyo equipment; Regression analysis; Software: Mitutoyo SJ communication tool; Microsoft Word; Microsoft Excel; SolidWorks.

5. This task assignment is an integral part of the final project

6. Project submission deadline: 20__ ________ __.

Given to the student Laurynas Turkas.

Task Assignment received____________________________ ________________________
(*Name, Surname of the Student*) (*Signature, date*)

Supervisor ____________________________ ________________________
(*Position, Name, Surname*) (*Signature, date*)

Laurynas Turkas „*Elektrokibirkštinio apdirbimo viela proceso eksperimentinis ir statistinis tyrimas*“ *Magistro* baigiamasis projektas / vadovas doc. dr. Povilas Krasauskas; Kauno technologijos universitetas, mechanikos inžinerijos ir dizaino fakultetas.

Studijų kryptis ir sritis: Gamybos inžinerija, Technologijos mokslai.

Reikšminiai žodžiai: *vielinis elektrokibirkštinis apdirbimas, pjovimo režimai, paviršiaus šiurkštumas, regresinė analizė*.

Kaunas, 2016. 59 p.

SANTRAUKA

Magistro baigiamajame darbe yra nagrinėjamas vielinio elektrokibirkštinio apdirbimo procesas. Darbe pateikiama apdirbimo būdo analizė, aprašomas veikimo principas, išanalizuojami apdirbimo įrankiai ir pateikiami apdirbimo metodo privalumai ir trūkumai. Technologinėje dalyje naudojant šį apdirbimo procesą buvo išpjauti titano GR-5 ruošiniai, keičiant skirtingus parametrus. Eksperimentinėje dalyje buvo matuotas gautas šiurkštumas ir tyriama jo priklausomybė nuo trijų skirtingų parametrų: pjovimo greičio, srovės stiprio ir vielos vyniojimo greičio. Darbo pabaigoje pateikiami gauti rezultatai ir atliekama regresinė analizė gautų rezultatų palyginimui bei pateikiamos projekto išvados.

Laurynas Turkas “*Experimental and Statistical Investigation of Wire Electrical Discharge Machining Process*” *Master's* thesis / supervisor assoc. prof. dr. Povilas Krasauskas. The Faculty of Mechanical Engineering and Design, Kaunas University of Technology.

Study area and field: Production and Manufacturing Engineering, Technological Sciences

Keywords: *wire electrical discharge machining, cutting regimes, surface roughness, regression analysis*.

Kaunas, 2016. 59 p.

SUMMARY

In this final Master‘s work there is being analyzed wire electrical discharge machining process. In this work there is presented analysis of machining process, described operation principle, the working tools are analized and there are presented the advantages and disadvantages of the process. In technological section using this machining process there were cut titanium GR-5 workpieces, while changing different parameters. In experimental part there was measured surface roughness and investigated its dependence on three different parameters: cutting speed, current strength and wire spinning speed. In the end of the work there are given results and done regression analysis for comparison of the results and later there are given project‘s conclusions.

CONTENTS

INTRODUCTION

Wire electrical discharge machining is a broadly acknowledged non-customary thermo-electrical material evacuation process used to fabricate parts with perplexing shapes and profiles. Wire EDM uses a persistently voyaging wire terminal made of flimsy copper, brass, molybdenum, tungsten of width 0,05 – 0,3 mm, which is fit for accomplishing little corner radius. The machining rule depends on disintegration of the workpiece material utilizing a progressive discrete releases happening between the wire and workpiece. The wire - cut uses deionized water as it‘s dielectric liquid. Likewise, the wire EDM procedure can machine not the usual and high strength and temperature resistive materials and dispose of the geometrical changes happening in the machining of warmth treated steels.

Talking about titanium alloys, nowadays there are more and more used non – traditional machining processes for this material machining, because of the poor machinability. The examples of non – traditional machining processes are laser cutting, plasma cutting, water - jet and wire EDM. The most precise and accurate process is wire EDM and that is why there is going to be used this process for machining of titanium alloy material in this project.

Aim of the project: to investigate experimentically and statistically titanium alloy‘s GR-5 surface roughness depending on wire EDM process parameters.

Structure of the project: this project consists of five parts: introduction, theoretical part, literature overview, experimental part and analysis part.

Requirements and conditions:

1. Literature overview;
2. Workpieces cutting using wire EDM;
3. Surface roughness mesurement using Mitutoyo equipment;
4. Regression analysis;
5. Software:
    - Mitutoyo SJ communication tool;
    - Microsoft Word;
    - Microsoft Excel;
    - SolidWorks.

Project volume: 50 figures and schemes, 11 tables, 9 formulas and 59 pages.

1. TITANIUM ALLOYS AND ITS MACHINABILITY

Titanium is the metal, that shows high strength and weight proportion, which is bolstered at lifted temperatures and it has surprising consumption resistance. Those parameters were primary reason of the snappy development of titanium industry in the most recent forty years. The principle field of material application is avionic business in air casings and motor segments. Non - aviation applications focal points are their ideal quality properties, in illustration: steam turbine sharp edges, super conductors, rockets et cetera. It likewise takes advantage in erosion resistance, in illustration: marine administrations, petrochemical, synthetic, power industry, biomedical instruments and etc.

In any case, regardless of the expanded titanium's use and creation, these materials are costly, when they are compared to different metals: because of multifaceted nature of the extraction procedure, issues amid manufacture and trouble of dissolving. Besides, as administration lives longer and property levels balance higher, the expenses of generation increments. In 1955, there was determined, that Ti and composites machining will dependably be issue and regardless, what systems would be utilized to change this material into chips. Poor titanium machinability drove a considerable measure of enormous organizations to put gigantic measures of cash in creating systems to decrease machining costs. These days, tool creators are searching for new device materials, which would recharge instrument life in such a test. [6, 10]

1.1. Titanium alloys structure

Alpha alloys

Pure titanium and alloyed titanium with α stabilizers, similar to tin and aluminum for instance: Ti-5Al-2,5Sn are delegated α composites. They are non - heat treatable and are for the most part simple to weld. They have from low to medium elasticity, great cut strength and flawless mechanical properties at cryogenic temperatures. [5, 10]

Titanium alloys

Pure titanium goes under the crystallographic change from hexagonal close stuffed to body focused cubic structure as its temperature is raised through 882° C. Alloying components, similar to tin don't change temperature of change when they are softened in titanium, however components like aluminum and oxygen may incite it to develop. These components are named alpha stabilizers. Components, that lower stage or temperature of change are called beta stabilizers. They are for the most part move metals. Business Ti amalgams are than named alpha, alpha - beta and beta.

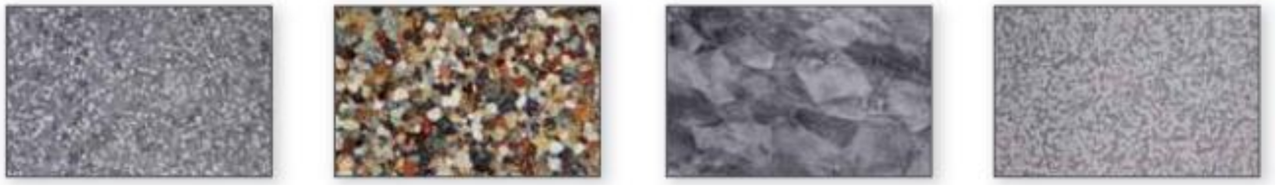
The alpha - beta combinations could incorporate close alpha and close beta amalgams, contingent upon their structure. [5, 10]

Beta alloys

Beta alloys contain move metals, for example, vanadium, niobium, tantalum and molybdenum, that settle the beta stage. The case of business beta compounds are: Ti-11,5Mo-6Zr-4,5Sn, Ti-15-V3-Cr3-Al3-Sn and Ti-5553. Beta compounds are effectively warm treatable, for the most part weldable and have high qualities. Good formability might be normal in the arrangement treated condition. Besides, beta combinations are at risk to flexible - fragile move and than are not appropriate for cryogenic applications. Beta composites are great in blend of properties for sheets, latches, overwhelming segments and spring applications. [5, 10]

Alpha - beta alloys

Those composites point alpha and beta stages and contain both alpha and beta stabilizers. The most well known and easiest compound in this gathering is Ti-6Al-4V, which is principally utilized as a part of the aeronautic trade. Combinations in this class are effortlessly formable and exhibit high room temperature quality and direct high temperature quality. The properties of those combinations could be changed through the warmth treatment. [5, 10]



a) b) c) d)

Fig. 1.1. Titanium alloys structure:

a) alpha alloy Ti-6Al-2Sn-4Zr-2, which shows alpha grains and a fine alpha - beta matrix structure; b) microstructure of alpha alloy Ti-5Al-2,5Sn; c) beta alloy Ti-3Al-8V-6Cr-4Mo-4Zr; d) Alpha - beta alloy Ti-6Al-4V, which shows primary alpha grains and a fine alpha - beta matrix structure [5]

Titanium and titanium alloys 110 - 450 HB, ≤48 HRC types:

- Pure: Ti-98,8, Ti-99,9.
- Alloyed: Ti-5Al-2,5Sn, Ti-6Al-4V, Ti-4Al-2Sn-4Zr-2Mo, Ti-3Al-8V-6Cr-4Mo-4Zr, Ti-10-V-2Fe-3Al, Ti-13V-11Cr-3Al, Ti-5Al-5Mo-5V-3Cr. [5]

Material characteristics:

- In comparison poor tool life;
- High chemical reactivity makes chips to rub and weld to cutting edges;
- Low thermal conductivity enlarges cutting temperatures;
- Manufactures abrasive, tough and stringy chips;
- Take precautionary measures, when reactive metal is being machined;
- Low elastic modulus simply promotes deflection of the workpiece;
- Easy work hardening. [5]

Table 1.1. Chemical composition of machined titanium [6]

Chemical element	Ti-6Al-4V (GR-5) (weight, %)
Al	5,5
V	3,8
Fe	Max 0,8
Mo	0
Cr	0
Nb	0
Zr	0

Table 1.2. Mechanical and thermal properties of Ti-6Al-4V [6]

Thermal and mechanical properties	Ti-6Al-4V (GR-5)
β transus (Tβ) (°C)	980
Density (g/cm3)	4,43
Tensile elastic modulus (GPa)	110
Compressive elastic modulus (GPa)	-
Tensile strength (MPa)	931
Yield strength (MPa)	862
Elongation (%)	14
Thermal conductivity at 20 °C (W/m K)	7,3
Specific heat 20–100 °C (J/Kg K)	709

1.1.1. Titanium alloys mechanical properties

Fundamental issues intrinsic to cutting procedure result, among different parameters, from undue temperature at the chip tool interface. The usage of enormous amount of cutting coolant liquids decreases cutting temperature, however brings about natural contamination and liquid sparing issues. The usage of new cutting tools are produced using propelled materials and better blend of slicing administrations elevated to essential, however in the meantime restricted advancement of machining procedure, especially in the event of Ti and its compounds.

Table 1.3. Titanium properties and influence on its machinability [8]

Properties	Description
Thermal conductivity	Low warm conductivity incites convergence of warmth on the tool cutting edge and face, impacting adversely the device life.
Chemical reactivity	Reactivity with normal gas, for example, oxygen, hydrogen and nitrogen prompts framing of oxides, hydrides and nitrides. Reactivity with cutting tool material incites rubbing, spreading and chipping of workpiece surface and quick apparatus wear.
Elastic modulus	Low flexible modulus permits thin deviation of workpiece under instrument weight, prompting the gab and resistance issues.
Hardness and strengh	High temperature strengh and hardness of Ti combinations require high cutting strength and than results in misshapening on cutting device amid cutting procedure. High dynamic shear strength amid cutting procedure instigates rough saw tooth edges and than produces tool indenting.
Work hardening	The specific work solidifying of Ti compounds incites non - attendance of developed edge before cutting tool and augment of the shearing edge, which thusly impels slight chip to contact an in correlation little range in cutting face, bringing about high bearing burdens per unit zone.

1.2. Titanium alloys machinability

Ti is one of the snappiest developing materials, which is used as a part of aviation applications. The prime method of reasoning for constructors to picked titanium in their ventures is its relative low mass for given quality level and its near imperviousness to high temperature. Titanium was used as a part of flying machine motor front areas and would proceed around there for the anticipated future. More over, because of properties of titanium material, these combinations will be more normal than any other time in recent memory in basic and landing gear parts. Notwithstanding, these combinations have additionally disadvantages. One of them is their poor machinability. [7]

Ti alloys processing is as particular as cutting of other high temperature materials. Titanium components are machined in the forged condition and often require removal of over ninety percent of weight of workpiece. High substance reactivity of Ti amalgams incites the chip to weld the instrument, prompting cratering and awkward tool wear. Low warm conductivity of those materials does not permit warmth being created, amid machining to expel from the tool edge. This can bring about a high device tip temperatures and undued instrument disfigurement and wear. Titanium combinations keep up quality at high temperatures and exhibit low warm conductivity. This particular property does not permit warmth being created amid machining procedure to expel from instrument edge, causing high device tip temperatures and undued plastic twisting wear, which prompts higher cutting powers. High work solidifying inclination of titanium combinations may likewise join to high cutting strengths and temperatures, that could prompt cut checking profundity. What is more, the contact zone of chip tool is in comparison small, resulting in big stress concentration due to those higher cutting forces and temperatures resulting in untimely failure of the cutting tool. The elasticity or Young's modulus of those materials provokes better spring of workpiece back and deviation of thin walled structures, resulting in tool vibration, chatter and poor finishing of surface. Alpha titanium alloys, like Ti-5Al-2,5S or Ti-8Al-1Mo-1V and others have in comparison low tensile strengths and produce lower cutting forces in comparison to that generated during machining of alpha - beta alloys, like Ti-6Al-4V and even lower as compared to beta alloys, like Ti-10V-2Fe-3Al and near beta alloys, like Ti-5553. Generous quantity of coolant fluid should be used with appropriate concentration to reduce high tool tip temperatures and fast tool wear. Positive rake sharp tools would lower cutting forces and temperatures and could reduce part deflection. [4, 5, 11]

1.2.1. Titanium machining problems

Even if, often one or few factors are reported to be those most responsible for the poor titanium machinability in fact many characteristics operate together to cause such metal to be classified as a hard to machine material. Main titanium machining problems are:

1. High strength is bolstered to enhance temperatures, that are produced amid machining procedure and this contradicts the plastic misshapening, which is expected to frame a chip.
2. Titanium's chip is dainty with thus not normally little contact region with instrument. This incites high weights on top of the instrument and slicing powers are accounted for to be like steel and henceforth the force utilization amid machining procedure is just about the same.
3. It has high coefficient of rubbing between device face and the chip.
4. There is an exceptional synthetic reactivity of Ti at the cutting temperature, more than 500° C with all device materials accessible.
5. Titanium's low volumetric particular warmth and generally little contact territory alongside the nearness of a meager stream zone between the chip and the instrument.
6. Low modulus of versatility, which may bring about gab, redirection and rubbing issues.
7. There must be taken think about titanium's propensity to light amid machining, because of included high temperatures.
8. There is high rate of work solidifying, additionally truth be told it solidifies to a less alongation, than steel.

Every one of these problems using together or at one time cause fast wear, chipping and may prompt calamitous wear of the tools.

2. ELECTRICAL DISCHARGE MACHINING PROCESS

In wire EDM process arrangement of electrical releases are delivered between precisely situated moving wire and the workpiece for machining material. Substituting or direct present and high recurrence heartbeats are released from the wire to workpiece with little start crevice over the protected dielectric fluid. A ton of flashes could be seen at one time. The volume of evacuated metal relies on upon the fancied cutting pace and the required surface completion.

The warmth of each electrical flash is around 14,000° to 20,000° Fahrenheit. It dissolves away little piece of material, which is eveporated and softened from the workpiece. Some wire material is dissolved away. These chips are flushed far from cutting zone with stream of deionized water crosswise over top and base flushing spouts.

2.1. Die - sinking wire EDM

In the die - sinker wire EDM process two metal components are overwhelmed in the protecting liquid and later associated with wellspring of current, which is exchanged on or off consequently, contingent upon the parameters, which are determined to the controller. There is an electric pressure made when the current is exchanged on and it is between two metal components and if the two sections are united to inside portion of an inch and electrical strain is released and start hops through it. At the spot where it is striked metal is being warmed up in particular and than it starts dissolving. [11]

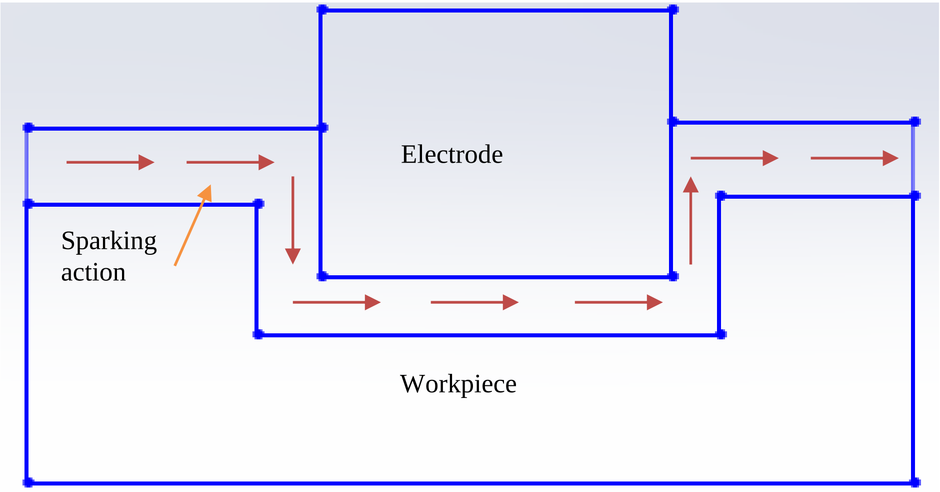


Fig. 2.1. Die - sinking wire EDM process scheme

Sinker EDM is called chamber sort EDM or mass volume EDM. It comprises of the electrode and workpiece, which are overwhelmed in the protecting liquid, for example, oil or other dielectric fluids. The anode and workpiece are associated with approapriate power supply. The force supply produces electrical potential between two components. At the point when the electrode gets to the workpiece dielectric breakdown happens in the fluid, shaping plasma channel and a little start bounced. Those sparks normally strike one at time. Those flashes happen in huge numbers at obviously irregular areas amongst anode and workpiece. At the point when the base of metal is dissolved and start crevice turns out to be in this way expanded the terminal is brought down naturally by the machine so that the procedure could proceed not interfered. A few 100000 flashes show up every second with the real obligation cycle, controlled by setup parameters. [11]

Die - sinking wire EDM parameters:

a) Spark on time or pulse time;
b) Spark off time or pause time;
c) Arc gap;
d) Discharge current;
e) Duty cycle;
f) Voltage;
g) Over cut.

Spark on time is the term of time, when current is permitted to stream per cycle. Material evacuation is straightforwardly corresponding to measure of vitality, which was connected amid on time. This vitality is controlled by crest current and length of on time.

Spark off time is the span of time in miniaturized scale seconds between flashes. This time lets liquid material to solidify and to be washed out of the circular segment crevice. This parameter is to influence speed and the steadiness of cutting. More over, if the off time is too short, it could incite sparks to be not steady.

The circular segment hole is the separation amongst anode and workpiece amid wire EDM operation. It can be called as flash crevice. Spark hole could be managed by a servo framework.

Current is measured in permitted ampers per cycle. Release current is specifically corresponding to the material evacuation rate.

Obligation cycle is the rate of the on time with respect to the aggregate process duration. This parameter can be ascertained partitioning on time by the aggregate process duration.

Voltage is potential, that might be measured by volts. This is the impact to the material evacuation rate and permitted to per cycle.

Over cut is clearance per side between electrode and the workpiece after the using of marching proces. [11]

2.2. Wire cut EDM process

Wire EDM is known as the spark EDM process. It is an electrical warm creation process, where meager single strand metal wire regarding deionized water, which is utilized to lead power and lets wire to cut over the metal by the warmth utilization from electrical flashes. Wire cut EDM is for the most part used to cut plates, such thickness as 300 millimeters and to make tools, punches and bites the dust from hard metals, that are difficult to machine utilizing different methodologies. Wire cut EDM is for the most part utilized, where are wanted low leftover burdens, since it does not require high cutting strengths for material evacuation. On the off chance that vitality or force per heartbeat is in correlation low as in completing operations, some progressions of the material are prospected in the mechanical properties because of low lingering burdens and material that has not been anxiety assuaged may degenerate in the machining operation. Because of the particular procedure properties, wire EDM procedure may effectively machine troublesome parts and precise segments out of hard conductive materials. [11, 24]

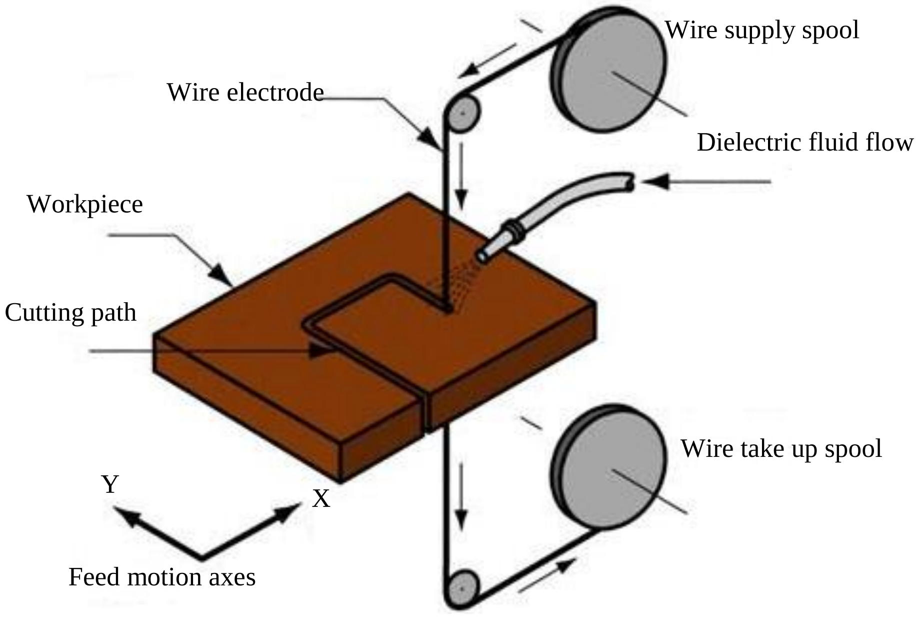


Fig. 2.2. Wire EDM cutting scheme [9]

2.3. Dry and near dry wire cut

There is a methodology in wire electrical discharge machining, which is led in gas environment without utilizing any dielectric fluid. This strategy is called dry wire EDM. As of late, new approach have presented in wire EDM, which is called close dry wire cut. In this methodology fluid dielectric liquid is supplanted by least amount of fluid with gas blend. There was found that in dry wire EDM vibration of wire terminal is insignificant because of the irrelevantly little process response power. Notwithstanding this, smaller crevice separation and no consumption for workpiece amid machining are different favorable circumstances of dry EDM. These attributes may enhance exactness and surface nature of workpiece amid completing the process of cutting. Fundamental disadvantages are lower material evacuation rate contrasted with routine wire EDM and stripes will probably be produced in this strategy. The disadvantages could be determined by expanding wire turning speed and diminishing genuine profundity of cut. [26]

There was examined completing cut with dry wire EDM and there was found that dry wire EDM has some focal points, similar to better straightness, lower surface roughness, shorter hole length. The principle detriment of this methodology was more awful material evacuation rate in correlation with ordinary technique. There was explored machining parameter impacts on surface roughness in dry and wet wire EDM. There was likewise found that wet wire electrical release machining gives better surface roughness contrasted with dry wire EDM.

More over, there was defined fast wire EDM in gas and emulsion fluid and trial results have appeared, that wire EDM in environment is putting forth arrangement of focal points, for example, better straightness precision and higher MMR. Rapid wire EDM in gas is showed in figure 2.3.

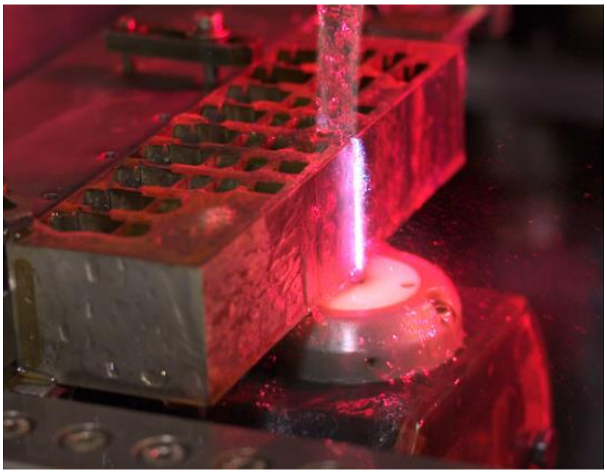


Fig. 2.3. Dry rapid wire EDM process [34]

2.4. Working principle of wire EDM

In this procedure metal is expelled from the workpiece because of disintegration, created by rapidly repeating flash release amongst tool and workpiece. Figure 2.4 shows mechanical and electrical parameters and electrical circuit of wire EDM process. A slight break around 0,025 mm is upheld amongst device and workpiece by servo framework, which is given in figure 2.4. Later, both tool and workpiece are overwhelmed in the dielectric liquid. Lamp fuel or wire EDM oil or deionized water is normal fluid sort dielectric and vaporous dielectrics could be utilized as a part of certain case. [11]

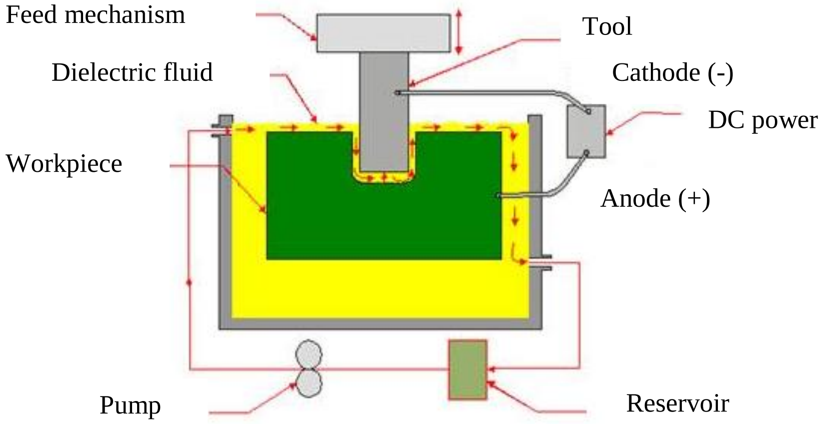


Fig. 2.4. Wire EDM process operation principle

Tool is cathode and workpiece is anode. At the point when voltage through the hole turns out to be sufficiently high it releases crosswise over hole as the flash in interim from 10 smaller scale seconds. The emphatically charged particles and electrons are quickened because of warmth, creating release channel, that gets to be conductive. It is now, when flash bounced, bringing about effects amongst particles and electrons and makes plasma channel. A brisk drop of prior channel electric resistance permits current thickness to achieve high values, delivering ionization increment and making of the effective attractive field. The minute flash happens, weight is produced enough between the workpiece and device and the outcome is that a high temperature is accomplished and at a such high weight and temperature some metal part is softened and disintegrated. Such apportioned compelling temperature rise prompts material evacuation. Material removal happens because of quick vaporization of the material and in addition because of dissolving. The liquid metal is evacuated just in part, not totally. [11, 30]

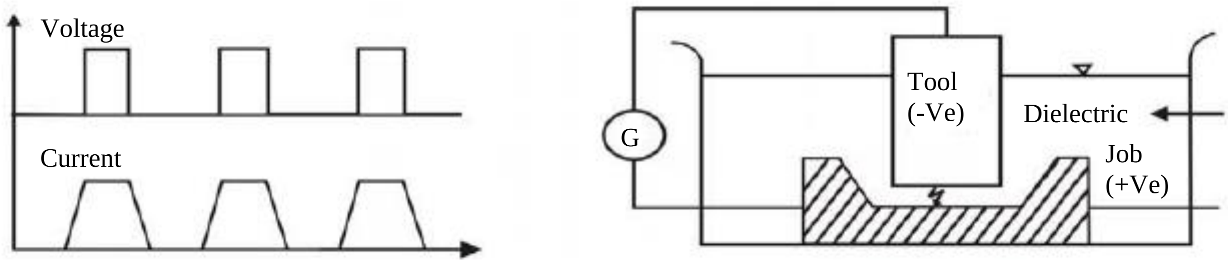


Fig. 2.5. Charge on tool and workpiece [11]

The potential difference is drawn and shown in figure 2.5. It is seen, that plasma channel is no more lasting. As the plasma channel falls flat it starts to produce weight or stun waves, which clears liquid material framing and expelled material cavity around the site of the spark. Wire EDM spark disintegration is the same as having an electrical short and than smolders little opening in the bit of metal it contacts. With the wire electrical discharge machining both workpiece and electrode materials must be power transmitters. [11, 12]

The wire EDM can be used in two fallowing ways:

1. A preshaped or framed cathode or device, more often than not is produced using graphite or copper and is molded to the type of cavity to duplicate. Framed electrode is bolstered vertically down and the converse state of the terminal is disintegrated or smoldered into strong workpiece.
2. A persistent voyaging vertical wire electrode and breadth of little needle is controlled by a PC to catch up customized way to dissolve or to cut tight opening over the workpiece to create the required shape.

Conventional wire EDM

An electric flash is used as a part of the wire EDM to cut the workpiece, which comes to fruition to the inverse cutting tool or anode. The terminal and workpiece are overwhelmed in the dielectric fluid, which is generally light greasing up oil. A servo component keeps up the space of flimsy thickness, which could resemble human hair amongst electrode and the workpiece, keeping them from reaching each other. In wire EDM can be utilized ram or sinker machining process and generally delicate graphite or metallic cathode to cut solidified steel or carbide. The wire EDM produces pit marginally greater, than terminal, because of the over cut. [12]

2.4.1. Dielectric fluids, flushing and wire cut EDM

The dielectric fluid must be flowed under steady weight to flush away metal components and backing in the machining or disintegration process. On the off chance that red flashes happen amid the cutting operation it implies, that the water supply is not sufficient. To beat this issue it is expected to expand the stream of water until blue flashes show up.

Amid the wire EDM process both workpiece and electrode are overwhelmed in the dielectric fluid or oil, which is electrical separator and controls circular segment release. Dielectric oil giving mean of flushing is pumped through the circular segment hole. This expels postponed components of workpiece material and electrode from the occupation chamber.

A standout amongst the most noteworthy elements in fruitful wire EDM procedure is the expulsion of the metal particles from working crevice. Flushing gets those particles out of the hole between the workpiece to keep them from framing connects, that may bring about shortcircuits.

Flushing is the most critical capacity in any wire EDM operation. Flushing is the procedure of exhibiting clean sifted dielectric liquid into the sparkle hole. Flushing connected in not effectively way could bring about scattered cutting and poor machining conditions.There are numbers of flushing approaches used to remove metal particles efficiently, while assisting in the machining operations. Too big liquid pressure would remove chips before they may lay in the cutting action and resulting in slower metal removal. Too small pressure would not remove chips rapildly enough and could result in short circuiting the erosion process.

The wire cut electrical discharge machining is a release machine, that utilizations CNC development to make fancied geometry or structure. It does not require an exceptional framed electrode, rather than this it utilizes the nonstop voyaging vertical wire under pressure as the terminal. The electrode in wire cut EDM is thick or it could be as a little as width needle, whose way is controlled by a machine PC to make the required geometry. [12]

2.5. Wire EDM parameters

Pulse on and off time

Wire EDM must happen on time and stop off time in turn amid machining. Amid on time voltage is connected to the crevice amongst workpiece and wire or terminal, while no voltage is set amid the off time. Therefore, electric discharge happens just for the term of the on time. More over, it could bring about a short out, bringing about wire breakage. To maintain a strategic distance from such circumstance, off time must be embedded as it is showed in figure 2.6. [26, 30]

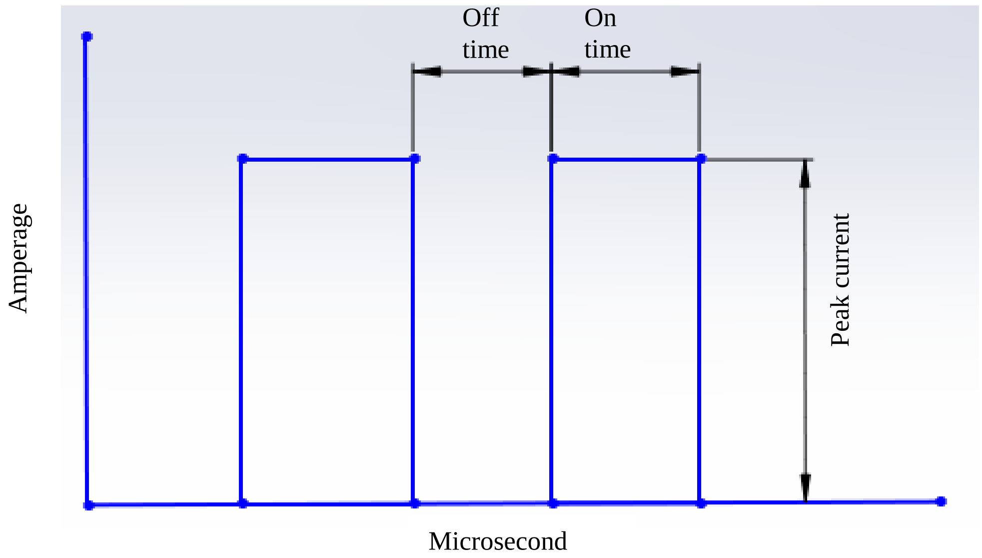


Fig. 2.6. Pulse on and off time

Gap voltage and peak current

Peak current is essentially the most huge machining parameter in wire EDM. It is measure of force, utilized as a part of wire EDM and measures it in amperage units. Amid every heartbeat on time, current increments before it achieves a level, which is communicated as the top current. Higher amperage is utilized as a part of rough operations and holes or subtle elements with immense surface ranges. Open circuit or crevice voltage indicates the supply voltage to be put on the hole. [26, 30]

Servo voltage and feed rate

Servo voltage parameter is used to control advances and withdraws of the wire. Amid operation machining voltage esteem differs relying upon the condition of the machining amongst electrode and workpiece. Servo voltage set up reference voltage to control advances and withdraws of the wire. On the off chance that machining voltage worth is higher than set voltage level, than wire progresses and in the event that it is lower, than wire withdraws. In addition, a higher servo voltage worth is, the more extensive hole between the workpiece and electrode gets to be. Higher servo voltage values decrease number of electric starts and settles electric release and the machining rate is backed off. Both servo feed rate and servo voltage can affect feed rate as it is shown in figure 2.7. [26, 30]

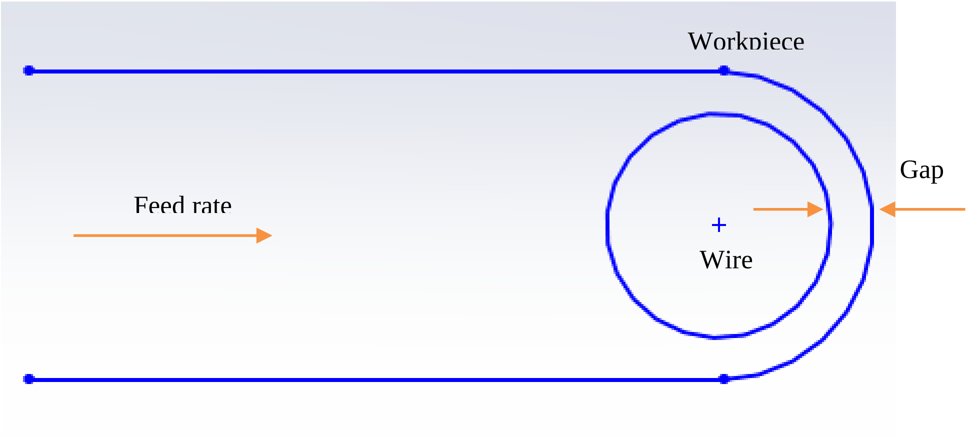


Fig. 2.7. Gap size and feed rate

Dielectric flow rate

Electrical discharge may happen noticeable all around. However, it is flimsy and cannot be used for machining operations. Dielectric fluid is required to get steady electric release. With dielectric fluid electric release machining might be balanced out with chip expulsion and effective cooling. Commonly, dionized water is utilized as a dielectric as a part of wire EDM because of it's natural inviting trademark. There is shown in figure 2.8 cutting line, while machining titanium alloy GR-5 utilizing typical flushing weight. This figure additionally indicates non - appearance of high blazing weight cutting line, which can't proceed with more than 1 mm. [26]

Fig. 2.8. Broken wire and small cutting line in titanium machining due to low flushing pressure [26]

Wire speed or wire feed rate

Speed of wire is likewise imperative parameter in wire EDM that demonstrates the rate of wire. As wire velocity builds wire utilization and expense of machining likewise increment, while low wire pace may bring about wire breakage at high cutting rate.

Wire tension

Wire tension is factor that may control the tension of wire in wire EDM. If wire tension is high, the wire stays straight, otherwise wire drags behind as it is shown in figure 2.9.

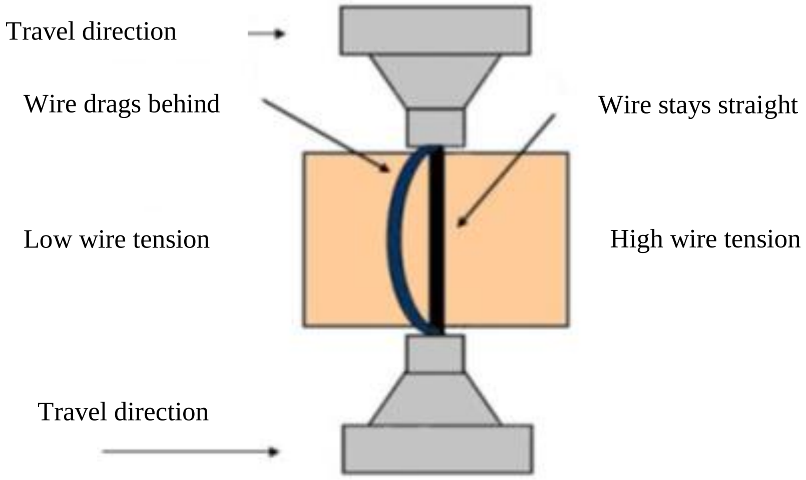


Fig. 2.9. Relation between wire tension and drag [26]

2.6. Wire materials

At the point when wire EDM was presented principle issue was material of wire, since this material ought to have a considerable measure of properties. Physical properties of wire EDM incorporate conductivity. A high conductivity rating is essential on the grounds that, hypothetically, it implies the wire can convey more present, which compares to a hotter start and expanded cutting pace. Elasticity, which shows a bility of wire to withstand the wire pressure, delegated upon the wire amid cutting, keeping in mind the end goal to make a straight cut. Stretching portrays the amount of wire gives or plastically misshapes just before it breaks. Dissolving point would incline toward that wire cathode would be something impervious to being liquefied too rapidly by electric flashes. Straightness is that it might wire to stay straight. The better flushablity quicker wire will cut and wire breakage chance will diminish. [26, 30]

Copper

Copper was the principal unique material used as a part of wire EDM. Despite the fact that, it's conductivity rating is great, low rigidity, high dissolving point and low vapor weight rating extremely constrained Copper's potential. Today copper's down to earth use is constrained to past machines with force supplies intended for copper wire.

Brass

Brass wire is a blend of zinc and copper, generally alloyed of 62 – 64 % Cu and 36 – 38 % Zn. Expansion of zinc gives higher elasticity, lower dissolving point and higher vapor weight rating, which more than counterbalances misfortunes in conductivity. Before long metal turned out to be most broadly utilized terminal material for universally useful in wire process. Presently it is financially accessible in extensive variety of hardness a resistances.

Coated wires

Since metal wires cannot be proficiently made with any higher convergence of zinc the following stride was the outline of covered wires, which are called plated wires. They have a center of metal or copper for conductivity and elasticity and are electro plated with immaculate or diffused zinc covering for enhanced flash development and flush qualities. Initially they are called speed wire because of their capacity to cut at essentially higher metal expulsion rates and covered wires are currently accessible in wide assortment of center materials, covering, covering materials, profundities and rigidities to suit distinctive applications and machine prerequisites. [26]

Although, coated wires are more costly than brass and as of now speak to the ideal decision for top all around execution. It was found that an expansion in efficiency of around 38 % for nickel based amalgam and 68 % for titanium composite was conceivable when supplanting standard not covered metal wire with Cu center covered wires dispersion use or tempered under the same working parameters. In layer thickness recast terms there were better results accomplished utilizing covered wire for both harsh and trim operations. Really, machining with covered wire around 24 % more slender recast for nickel based combination and 39 % more slender for titanium composite have delivered. [26]

Fine wires

Ordinarily wire distances across are 0,015 – 0,03 milimiters. High exactness take a shot at wire EDM machines, requiring little inside sweep and calls for wire distances across 0,002 – 0,01 milimiters. Molybdenum and tungsten wires are used, on the grounds that metal and covered wires are not down to earth, because of their low load conveying limit in these sizes. In addition, because of restricted conductivity, high dissolving focuses and low vapor weight appraisals are not appropriate for thick work and tends to cut gradually. Up to this point, just couple of experimental works have been managing cutting by wire EDM utilizing wires with distance across underneath fifty micrometers. Wire materials are tungsten with high rigidity and dissolving temperature and metal covered steel wire. Regular slim wire widths are 20, 25, 30 and 50 micrometers. These wires could be utilized to make small scale parts with wire EDM. [26]

2.7. Wire EDM machine composition

Wire and vertical EDM machines are given a servo control instrument, that consequently manages a consistent hole of so little thickness that it could resemble human hair amongst electrode and workpiece. It is noteworthy for both machine sorts, that there is no physical contact amongst electrode and workpiece, on the grounds that generally arcing would harm workpiece and break the wire. The servo system advances cathode into the workpiece like the operation continues and faculties the work wire separating and controls it to support the correct curve hole, which is key to fruitful machining process. [12]

Wire electrical discharge machines are made in various sizes and styles of flush or overwhelmed sort machines to fit the shopper needs. Huge scale electrical release machines may handle workpieces weighing more than 10,000 pounds and may cut more than 20 inches of thickness. Programmed wire strings are for the most part standard gear in many models. Notwithstanding the X and Y table ventures, wire electrical discharge machines have U and V flies out for giving development to cut decreases. Most machines can slice decreases from 20 to 30 degrees, contingent upon workpiece thickness. [13]

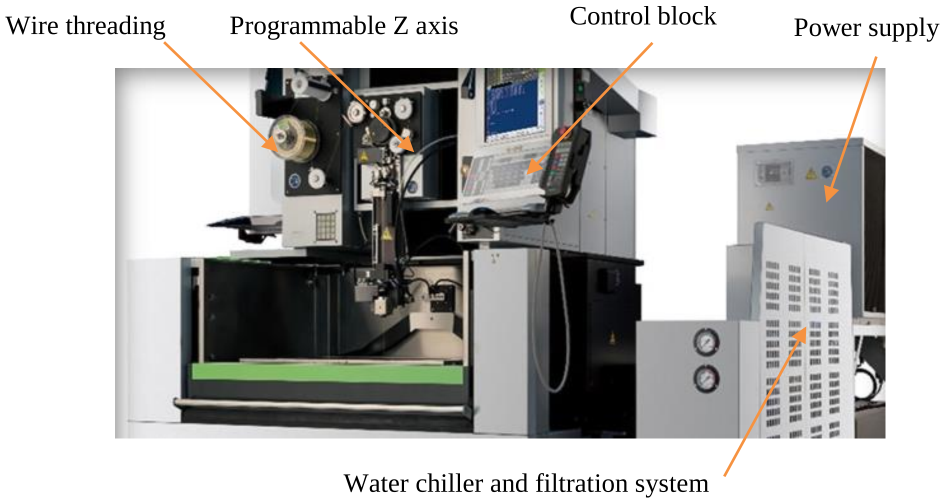


Fig. 2.10. Wire EDM technology [33]

Figure 2.10 represents current wire EDM process technology. The system consists of a CNC power supply with anti electrolysis circuit, automatic wire threading, control block, programmable Z axis, water chiller and filtration system. [13]

Fig. 2.11. Wire EDM machine [14]

A wire EDM system consists of four major components:

1. Computerized numerical control or CNC. This is the brain.
2. Power supply provides energy to the spark. This is the muscle.
3. Mechanical section. Work table, work stand, taper unit and wire drive mechanism. All this are actual machine tool. All this is the body.
4. Dielectric system. The water reservoir, where filtration, condition of the water and temperature of the water is equipted and sustained. This is the alimentation. [13]

There are two types of wire EDM process:

1. Die - sinking wire EDM.
2. Wire - cut EDM.

Each of them is used to manufaure small and precise parts, such as large items, like automotive stamping dies and aircraft body components. The biggest single usage of wire electrical discharge mahining is in die making. [11]

2.8. Principles of operation

The primary parts of wire EDM framework are illustrated in figure 2.12. The workpiece is fitted on the machine device table and the electrode is affectionated to the ram of the machine. A DC servo unit or water driven chamber moves the ram and cathode in a vertical movement and supports better position of the electrode in connection with workpiece. The area is controlled naturally with enormous precision by the servo framework and force supply.

Amid ordinary operations terminal never touches the workpiece, however it is isolated by little start crevice. At the point when operation is in advancement, the ram moves terminal towards the workpiece until the space between them turns out to be such that voltage in the hole coud ionize the dielectric fluid and permit the electrical release or start to go from electrode to workpiece. [11]

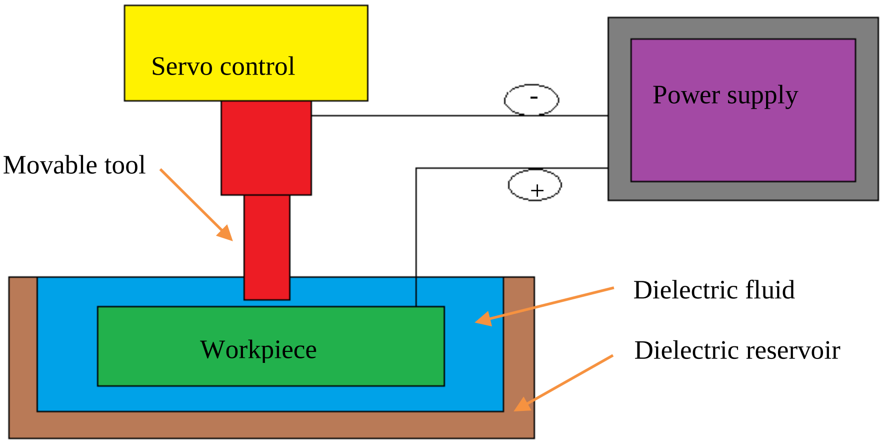


Fig. 2.12. Wire EDM servo control mechanism

Every release softens or vaporizes little region of the workpiece surface. This liquid metal is later cooled in the dielectric quid and sets into little round molecule, which later is flushed away by weight or movement of the dielectric. The effect of every heartbeat is separated to an extremely limited region and the area, which is dictated by the shape and anode position. Both workpiece and terminal are overwhelmed in the dielectric fluid, which goes about as electrical protector to control sparkle releases. In wire EDM process dielectric fluid likewise performs the capacity of a coolant medium and declines high temperatures in the circular segment hole. Besides, dielectric fluid is pumped accross the circular segment hole to flush away the dissolved components amongst workpiece and electrode. Proper flushing is basic to high metal expulsion rates and great machining conditions. [11]

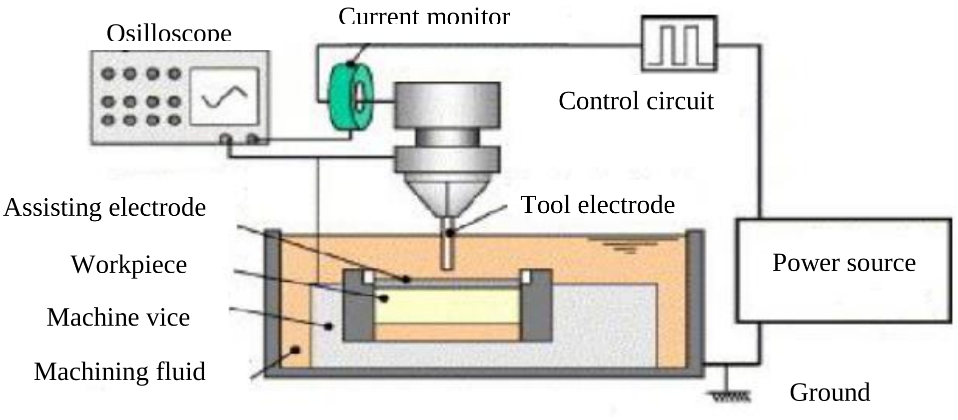


Fig. 2.13. Complete wire EDM system [11]

It is known, that wire EDM disintegrates metal with electrical releases and does not with chip machining cutting tools. Workpiece hardness does not decide, whether material might be machined by wire EDM or not. It disposes of the danger of harm or twisting, which may scrap a costly workpiece amid warmth treating.

2.9. Wire EDM application

The wire EDM is turning into the regular methodology of making tests and generation components for the most part in the aviation, car and gadgets commercial ventures, where creation amounts are generally low. Wire EDM application:

1. This operation is used to machine hard materials, that are difficult to machine, for example, composites, tungsten carbides, apparatus steels and the others.Wire EDM is used for forging operations or extrusion and wire drawing processes or thread cutting.
2. This procedure is used for bended openings boring operations.
3. Wire EDM is used for inside string cutting and helical rigging cutting operations.
4. This procedure is used for sharp edges and corners machining, that may not be machined successfully by the other machining operations.
5. Using wire EDM higher points of confinement of resilience might be acquired. Additionally, territories, that require higher surface accuracy are utilizing wire EDM operation.
6. Ceramic materials, that are difficult to machine might be machined by the wire EDM. Wire EDM has made its presence felt in the new fields such as sports, medical and surgical, tools, optical, including automotive redesign and development areas.

7. This is a promising method to meet expanding requests for littler segments and is normally profoundly muddled and multi utilitarian parts used as a part of the region of small scale hardware. [11]

2.9.1. Wire EDM advantages, disadvantages and limitation

Ordinary wire EDM machines might be customized for rotational or vertical machining, orbital or directional, vectorial or cone shaped, helical, turn and indexing machining cycles. This assortment gives wire EDM a great deal of points of interest over ordinary machine tools:

1. Any material, that is electrically conductive may be cut using wire EDM.
2. Hardened workpieces may be machined and the deformation, which is provoked by heat treatment is removed.
3. X, Y and Z axes movements allow to program complex profiles using simple electrode.
4. Diffucult dies sections and molds may be produced precisely, faster and with lower costs.
5. Thin fragile sections, such as webs and fins may be machined without deforming the element.

Main wire EDM disadvantages are:

1. Wear rate on the cathode is much higher. Now and then to complete the occupation it could be important to utilize more than one terminal.
2. Using wire EDM the workpiece ought to be electrically conductive.
3. The vitality required for the operation is more than that of the ordinary procedure and consequently will be more costly.

Wire EDM limitation

1. The need for electrical conductivity.

The workpiece must be electrically conductive to make releases. Isolators, for example, glass, plastics and most earthenware production may not be machined by wire EDM and for instance precious stone is known as special case. Machining of sectional conductors like semi conductors or somewhat conductive pottery and glass is additionally conceivable.

2. Predictability of the gap.

The gap dimensions are not always easily predictable, especially with difficult geometry of workpiece.

3. Low material removal rate.

The wire EDM material evacuation is low, particularly if there should arise an occurrence of bite the dust - sinking wire EDM, where absolute pit volume must be expelled by liquefying operation or using dissipating process. Using wire EDM coveted workpiece diagram geometry must be machined. Because of the low material evacuation rate, wire EDM is for the most part restricted to the assembling of little arrangement.

4. Electrical parameters optimization.

The electrical parameters decision of wire EDM relies on upon material blend of electrode and workpiece. Wire EDM produces supply those parameters for constrained amount of material mixes. At the point when unique composites are being machined, the client needs to plan his own innovation.

5. Zone affected by heat near cutting edges.
6. Dielectric vapour may be dangerous.

3. LITERATURE OVERVIEW

Wire EDM is thermo electrical procedure, where material is disintegrated by arrangement of flashes amongst workpiece and the wire electrode. The wire and part are sinked in dielectric liquid, which goes about as the coolant and flushes away wrecks. The development of wire is numerically controlled to accomplish fancied three - dimensional shape and high exactness of the workpiece. Wire EDM is not new procedure of machining. This procedure was actualized in the 1960's and has altered the tools, bite the dust, shape, and metal working businesses. It is the most energizing machine instrument produced for this industry in the most recent fifty years and has assortment of points of interest to offer. In this procedure is no contact amongst workpiece and cathode, therefore materials of any hardness might be cut while they can direct power. Besides, wire does not touch the workpiece - there is no physical weight passed on the workpiece and measure of clasping weight required to hold the workpiece is negligible. Despite the fact that, the electrical conductivity is noteworthy trademark in this sort of machining and a few methods can be used to build proficiency in machining of low electrical conductive materials. The spark hypothesis on a wire EDM is essentially the same as that of the vertical EDM. A great deal of flashes can be seen at one time. This is on the grounds that real releases can happen more than 100000 times each second. Warmth of each electrical flash, evaluated at around 15,000° to 21,000° Fahrenheit. This procedure has been utilized as a part of aviation, car and atomic commercial enterprises to machine correctly perplexing and sporadic shapes in different hard to machine electrically con-ductive materials. As of late, wire EDM is being used to create a wide assortment of scaled down and miniaturized scale parts in combinations, metals, sintered materials, earthenware production, established carbides and silicon. These attributes make wire EDM a procedure, which has stayed as a focused and efficient machining choice fullfilling the requesting machining prerequisites selected by developing cost weights and short item advancement cycles. [26]

Numerous scientists attempted to augment material evacuation rate and cutting rate using different methodologies. Because of these elements it might increment monetary advantages in wire EDM impressively. Verging on both elements decide the same wonder, which is machining rate. Material removal rate worth is acquired by taking after condition:

$$MR = \frac{W_b - W_a}{T\rho}, \tag{3.1}$$

where: W_b - workpiece weight before machining; W_a - workpiece weight after machining; T - machining time; ρ- material density.

There was analyzed wire breakage phenomenon with the thermal model and experimental investigations. There was found, that material removal rate increases initially in wire EDM with reduction of pulse off time. Of course, at a very short pulse off time gap becomes not stable, which leads to reduction in the machining rate.

There were presented process parameter effects on material removal rate in wire EDM and it was found that, when pulse on time and peak current increase, material removal rate increases too and also increases pulse off time and servo voltage and material removal rate decreases. [26]

There was explored impacts of wire and workpiece material on wire EDM productivity, it additionally was found, that higher estimation of warm conduction, particular warmth limit of machined material would bring about the diminishment of effectiveness of wire electrical released machining. Besides, it was found, that warm conductivity and particular warmth ended up being most imperative elements in workpiece, which may decide material expulsion rate and volume of warmth zone. There was made an endeavor to decide noteworthy parameters of procedure for execution measures, for example, material evacuation rate, surface completion and kerf width in the wire EDM. Components, similar to heartbeat term, release current and dielectric stream rate and their connections were found to assume vital part in harsh cutting procedures for amplification MRR. [17, 22, 23, 26]

There was investigated workpiece thickness impact on the material expulsion rate and was normal, that this component was a huge, while as per examination workpiece thickness is not critical element for MRR. Arrangement was done of different potential components, which are influencing wire edm execution measures into 5 noteworthy gatherings. W_b and W_a are weight of workpiece material before egories namely the various properties of workpiece material and after machining. T – machining time in seconds and dielectric fluid, machine characteristics, adjustable machine and ρ– material density of the workpiece. Cutting pace figures isolating a cutting length by comparing cutting time. Taking into account the hypothesis, expanding top current can build the vitality of release and creates more extensive and more profound cavities that bring about to high MMR. Expanding beat on time may build the term of release that could build MMR. There was introduced examination of advancing machining parameter consequences for the kerf and the material evacuation rate. There was resolved level of significance of the machining parameters on the material expulsion rate using ANOVA [21, 22]. There was found that open circuit voltage and heartbeat term were exceptionally viable parameters, where wire velocity and dielectric flushing weight were less powerful elements. As indicated by exploration open circuit voltage for controlling material expulsion rate was 6 times more critical than heartbeat term. Notwithstanding this, there was connected trials advancement strategy to think about and upgrade the conceivable impacts of variables amid procedure plan and advancement and accepted trial results utilizing clamor - to - sign or S/N analysis. [17, 22, 23, 26]

Numerous scientists attempted to minimize surface roughness using different methodologies. In view of hypothesis, surface roughness was influenced by heartbeat on time and top current and the cutting speed and surface roughness had an opposite relationship. An examination appeared, that surface roughness decreases when cutting velocity increments. As per different inquires about, heartbeat on time is the most huge variable that influences surface roughness. At the point when heartbeat on time expands surface roughness increments too because of twofold starting. At the end of the day it would seem like this: twofold starting and confined starting turn out to be more regular as the beat on time increments. Twofold starting produces poor surface completion. [16, 19, 26]

There was affirmed that heartbeat on time is the most noteworthy parameter that impacts surface roughness took after by top current for zinc covered wire. There was found that heartbeat on time and top current have critical impact on surface roughness and when these variables build the surface roughness gets to be bigger. There was affirmed that bigger heartbeat on time and top current would bring about twofold starting, which expands the estimation of surface roughness. There was examined cutting parameter consequences for size of disintegration cavities on wire electrode. An examination of wire electrode pits is critical for comprehension wire breakage, kerf size and surface roughness of the workpiece. Bigger sizes of holes on the wire build the danger of wire breakage and result in poor workpiece surface quality and exactness of machining. It is found that expanding beat span, open circuit voltage and wire speed builds the pit size, where expanding dielectric flushing weight diminishes pit size. There was observed that, elements like top current and heartbeat on time are generally imperative. Wire strain and servo voltage are critical and beat off time, flushing weight and wire rate are less noteworthy components that influence surface roughness. There was explored different elements impacts on surface roughness. It was uncovered that surface roughness increments when the beat term and open circuit voltage increments. It gave the idea that surface roughness relies on upon these parameters and dielectric fluid weight and wire velocity are not appeared to have more impact. [16, 19, 25, 26]

There was contemplated impacts of 6 included elements: discharge current, beat span, beat recurrence, wire speed, wire pressure and dielectric stream rate on surface roughness and MMR. There was found, that variables like discharge current, beat span, dielectric stream rate and communications between them assume noteworthy part in surface roughness and MMR. There was explored impact of heartbeat span, open circuit voltage, wire rate and dielectric flushing weight on the wire EDM workpiece surface roughness. It was likewise found, that as heartbeat term builds, open circuit voltage and wire speed increments with the surface roughness, where expanded dielectric fluid weight diminishes surface roughness. [16, 19]

Kerf width and sparging gap explore the same marvel as it is showed in figure 3.1 and it is estimation measure of material that is squandered amid procedure. It might decide dimensional accuracy of the completing part and the inside corner sweep of the item in wire electrical discharge machining operations and are constrained by this. Taking after condition is used to decide sparking gap esteem: [18, 26]

$$S_g = \frac{A_{kw} - d_w}{2}, \tag{3.2}$$

where: A_{kw} – average of kerf width; d_w – wire diameter.

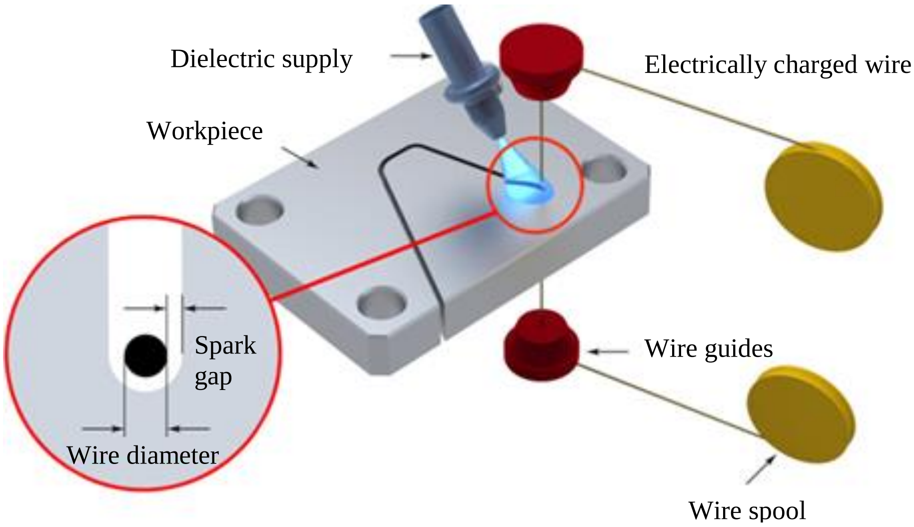


Fig. 3.1. Sparking gap details [35]

There are some different reports about heartbeat off time span, top current and dielectric flushing weight for their impact on kerf width. There was researched wire EDM parameter consequences for kerf width, while machining stainless steel. It was found, that heartbeat on time and dielectric flushing weight are the most noteworthy elements, while crevice voltage, beat off time and wire nourish rate are the less imperative parameter on the kerf width. There was introduced significance level examination of the machining parameters on kerf width utilizing investigation of change. It was likewise found, that open circuit voltage and heartbeat span were exceedingly successful parameters, where wire rate and dielectric flushing weight were less viable parameters.

As indicated by examination, open circuit voltage to control kerf width was just about three times more critical than heartbeat length. There was additionally contemplated kerf width and it was found that hole voltage is the critical element that influences kerf width and heartbeat on time and heartbeat off time are not vital. [18, 26, 28]

Few researchers tried to minimize wire wear ratio using different methods, because this factor may help to reduce wire breakage phenomenon considerably. Wire wear ratio can be obtained by the following equation:

$$W_{rr} = \frac{W_{wl}}{I_{ww}}, \tag{3.3}$$

where: W_{wl} - wire weight loss, I_{ww} - initial wire weight.

There was explored diverse wire electrical discharge machining parameters consequences for wire wear proportion and it was found that expanding beat length and open circuit voltage build the wire wear proportion, where expanding wire rate and dielectric fluid weight diminish it. If there should arise an occurrence of orthogonal corners answer for this issue is quite straightforward and straight forward, which is over travel technique. What is more, things get confused, when cutting is craved along a bend. There was explored of various wire EDM parameters impact on wire slack, amid rough cut and trim cut procedures. It was found that heartbeat on time, beat off time and heartbeat crest current amid rough cutting and heartbeat crest voltage, wire strain, servo flash hole set voltage amid trim cutting are essential elements. [26, 27]

To improve surface integrity of the wire EDM factors like surface roughness, white layer thickness and surface crack should be considered. High quality surface roughness may be escorted by high material removal rate and high ratio value. [26]

Wire EDM is very useful wherever complex geometry with tight tolerances needed to be generated. In this condition, geometrical inaccuracies are completely not acceptable. Some of the researchers tried to minimize wire lag, because geometrical inaccuracy could be caused due to this phenomenon, however still there is lack of information about this fact. More researches about wire lag could help improve precition in contour cutting with wire EDM. Wire lag phenomenon is given in figure 3.2. [26]

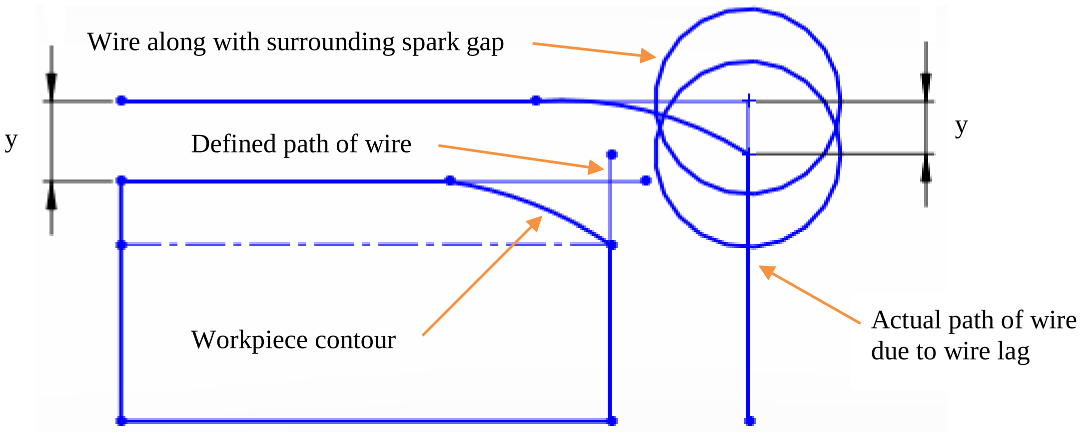


Fig. 3.2. Wire lag phenomenon

Wire lag is measured using profile projector by measuring the projection image of workpiece. There was investigated different parameter effects on surface characteristics of GR-5. It is observed that more uniform surface parameters are received using electrode of coated wire. What is more, it was found that pulse off time is the most sensitive parameter that influences layer formation, consisting of oxides mixture. With a lower value of pulse of time, a considerable decrease in the formation of oxides may be obtained. [26]

Notwithstanding this, there was uncovered that parameters, for example, beat off time, beat on time, wire speed, dielectric flushing weights and wire strain are recognized as imperative parameters of wire EDM. There was contemplated process parameter impact on the development and qualities of amendment layer and in term of revision layer was found that crest discharge current and heartbeat on time were the primary variables in deciding normal rectification layer thickness and heartbeat off time. Wire distance across have not showed noteworthy impact all things considered remedy layer thickness. There has been made an endeavor to model white layer profundity through reaction surface methodology in a wire electrical discharge machining containing harsh cut, trailed by the trim cut. There was likewise found, that white layer profundity increments with expanding heartbeat on time amid the primary cut and it diminishes with expanding heartbeat on time, while trim cutting is in advancement. Notwithstanding this, when cutting velocity increments in trim cutting, the white layer profundity first lessens and after that begins expanding. There was examined surface roughness of AISI 4140 steel in wire EDM and it can be finished up, that heartbeat on length has real impact in characterizing the wire EDM surface composition when contrasted with the top current. [26]

4. EXPERIMENTAL PART

4.1. Workpiece preparation

Using wire electrical discharge machining there was cut titanium GR-5 workpiece. From this workpiece there were cut three pentagons. To start wire electrical discharge machining first there has to be blind hole, where the wire will be entered through. Than cutting begins and the wire goes around all five sides and cuts out pentagon.

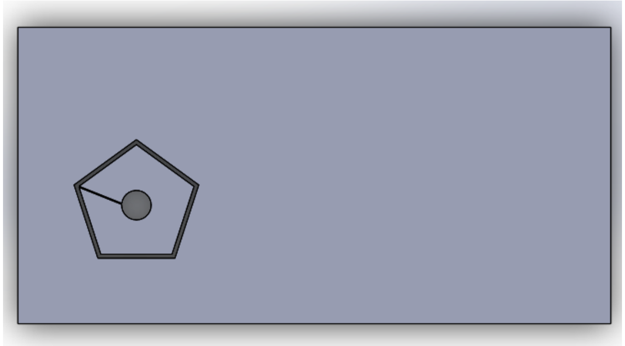


Fig. 4.1. Wire EDM workpiece cutting sketch

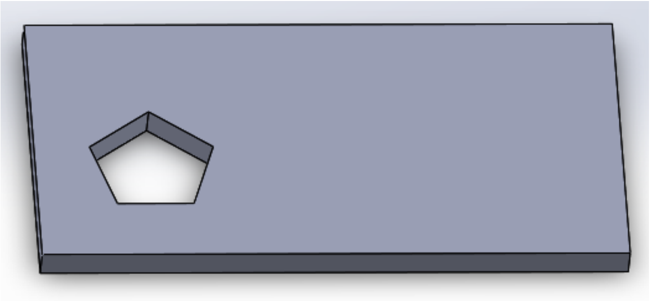


Fig. 4.2. Workpiece material

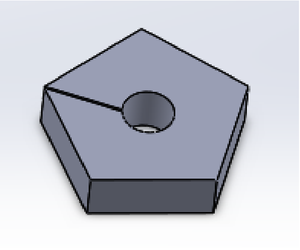


Fig. 4.3. Workpiece

Fig. 4.4. Workpieces

Fig. 4.5. Material titanium GR-5

Table 4.1. Cutting parameters

Surface number	**Cutting speed, m/min**	**Current strength, A**	**Wire spinning speed, m/min**
1	1	2	5
2	2	6	7
3	3	8	9
4	4	12	11
5	5	16	13

Wire electrical discharge machining cutting process example is shown in figure 4.6.

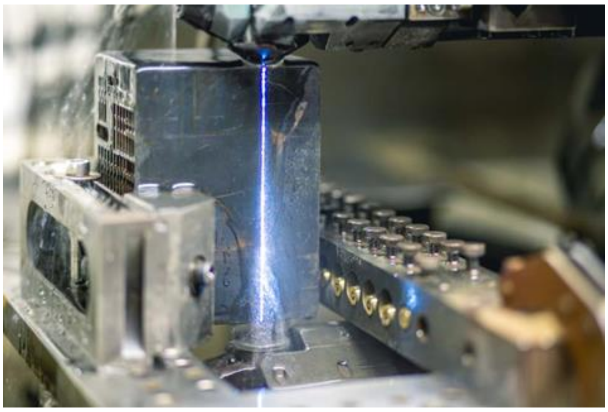


Fig. 4.6. Wire EDM process [15]

4.2. Experiment technique

Surface roughness of titanium GR-5 was measured using Surftest SJ-210 Mitutoyo equipment. The Surftest SJ-210 complies with the following standarts: JIS (JIS-B0601-2001, JIS-B0601-1994, JIS-B0601-1982), VDA, ISO-1997 and ANSI. [32]

In addition to calculation results the Surftest SJ-210 can display sectional calculation results and assesed profiles, load curves and amplitude distribution curves.

In this titanium surface roughness research was used standart drive unit. The drive unit is put on surface, which‘s roughness has to be measured. During measurement process the drive unit goes trough all surface and sends information to device. The drive unit is the most important part of the surftest SJ-210 device. [32]

Fig. 4.7. Standart drive unit [32]

Fig. 4.8. Surftest SJ-210 roughness measurement device [32]

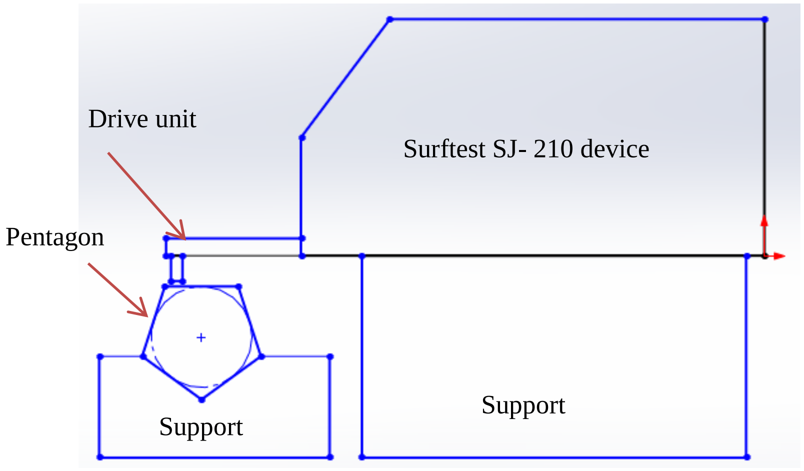


Fig. 4.9. Pentagon surface roughness measurement sketch

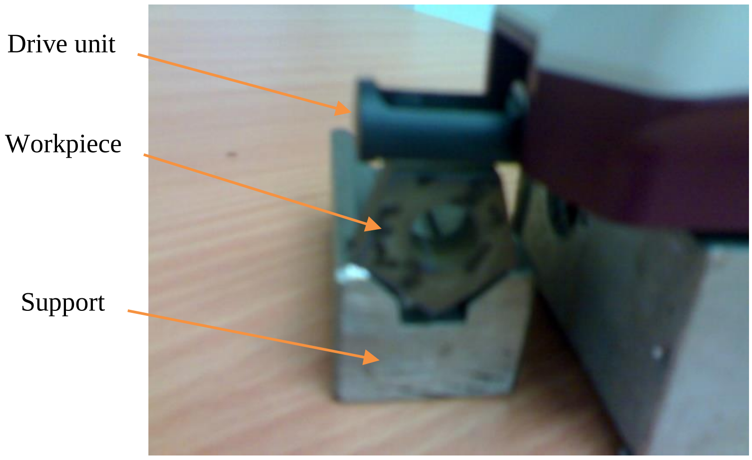


Fig. 4.10. Front view of the measurement drive unit on the workpiece surface

Figure 4.10 represents surface roughness measurement procedure. Workpiece and measurement device are put on supports to reach appropriate height between workpiece surface and drive unit. When this is ready, surface measurement begins: a small needle of drive unit touches the surface and goes through all it to the next corner and than goes back to the primary position.

Fig. 4.11. Top view of the measurement drive unit on the workpiece surface

Fig. 4.12. Surftest SJ-210 device and workpieces

Fig. 4.13. Surftest SJ-210 device showing the results

Fig. 4.14. Surftest SJ-210 device connected to laptop

To connect Surftest SJ-210 device to laptop there must be installed Mitutoyo Surftest SJ-210 communication tool software in laptop. Than, surface measurement device can be connected to laptop. When there is a connection between laptop and Surftest SJ-210 device the measurement procedure may be started. Surftest SJ-210 device drive unit measures the surface roughness and than sends generated data to laptop.

4.3. Experiment results

There were done three surface roughness measurements depending on the cutting speed, current stength and wire spinning speed. Each surface of the all three workpieces was measured three times and later there was calculated average. The results are given in table 4.2, table 4.3 and table 4.4.

Workpiece number 1. Surface roughness depending on cutting speed.

Table 4.2. Roughness measurement results

Surface number	**Cutting speed, m/min**	**Roughness, Ra I measurement results**	**Roughness, Ra II measurement results**	**Roughness, Ra III measurement results**	**Roughness, Ra Measurements average**
1	1	2,647	2,734	2,585	2,655
2	2	2,587	2,863	2,662	2,704
3	3	2,884	2,748	2,862	2,831
4	4	2,953	2,873	2,915	2,914
5	5	3,097	3,1	3,116	3,104

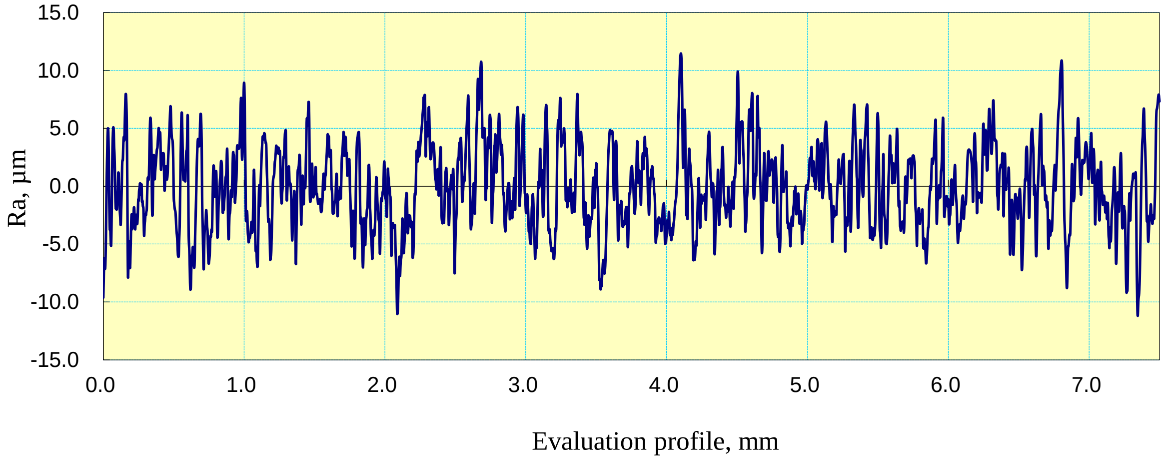


Fig. 4.15. Surface No. 1 evaluation profile graph

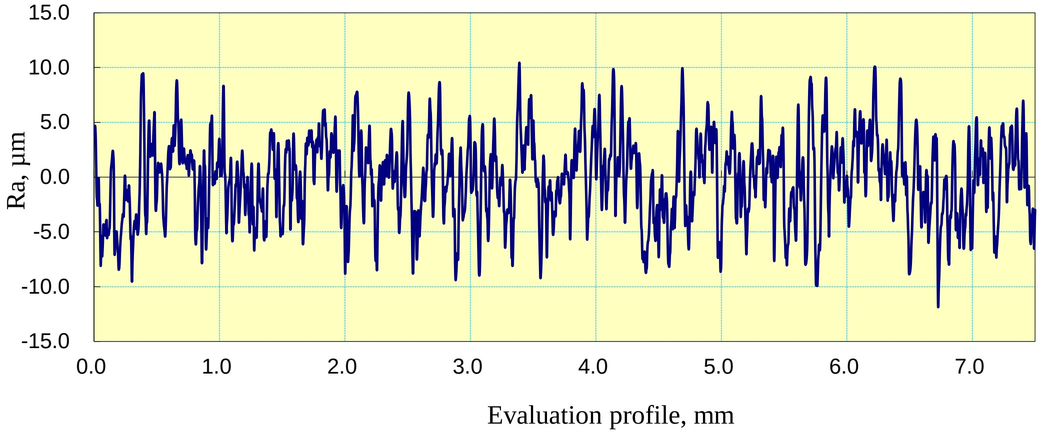


Fig. 4.16. Surface No. 2 evaluation profile graph

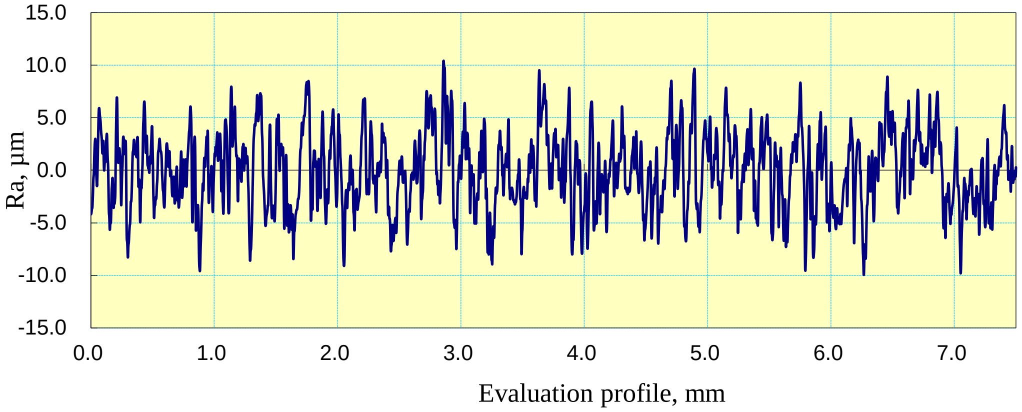


Fig. 4.17. Surface No. 3 evaluation profile graph

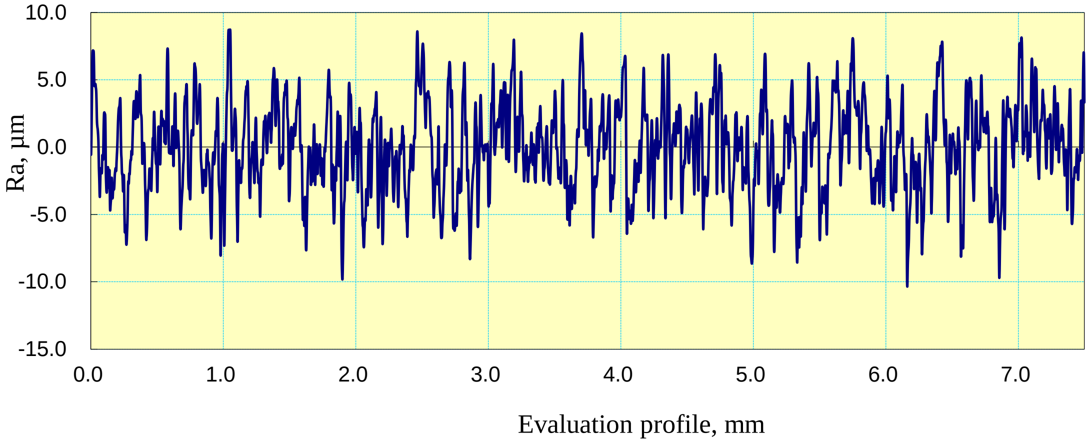


Fig. 4.18. Surface No. 4 evaluation profile graph

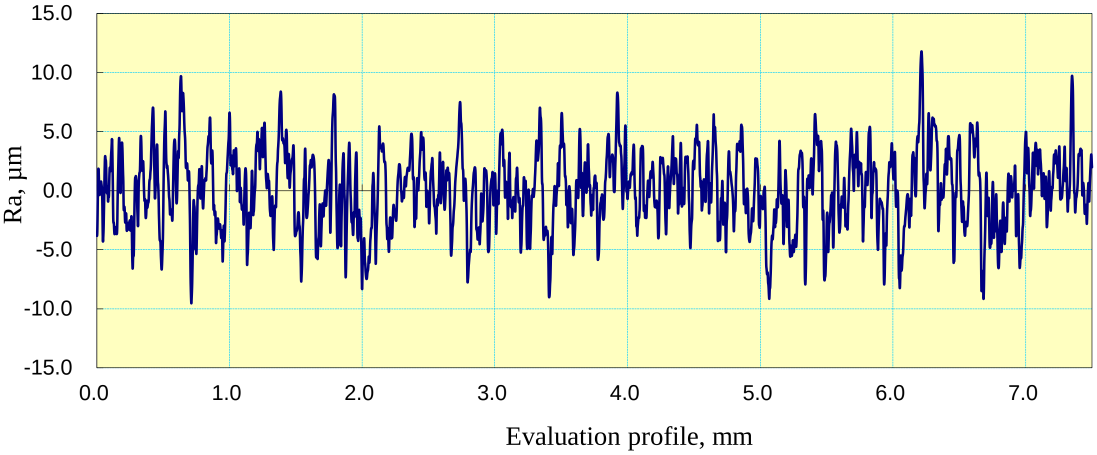


Fig. 4.19. Surface No. 5 evaluation profile graph

Later, there was drawn graph showing surface roughness dependence on cutting speed.

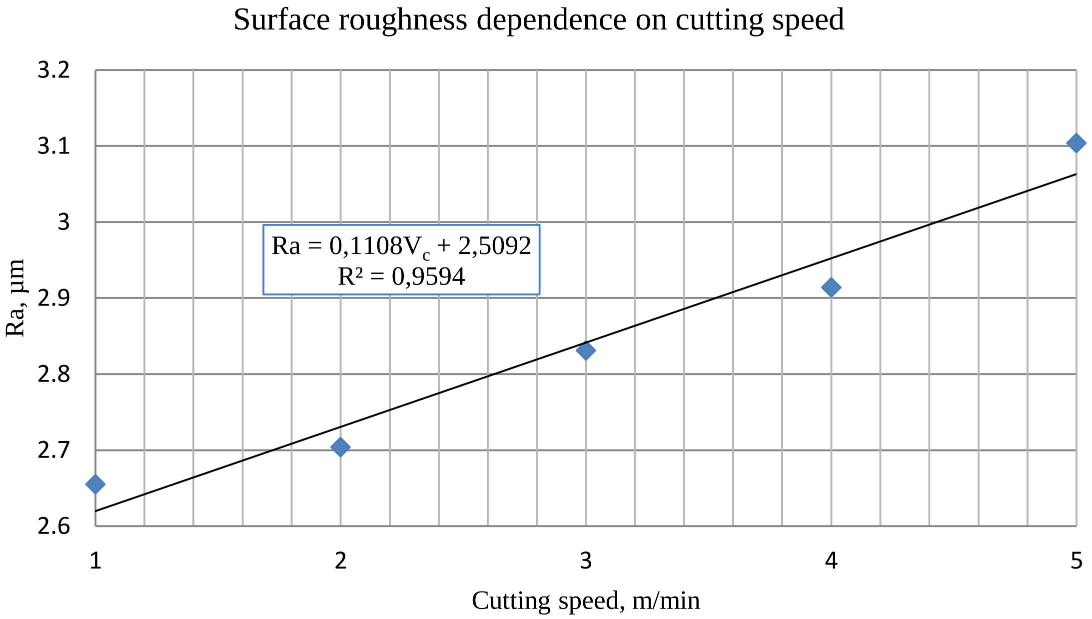


Fig. 4.20. Surface roughness dependence on cutting speed

It is seen from figure 4.20, that the surface roughness dependence on cutting speed is linear. The formula of linear dependence is:

$$Ra = 0{,}1108V_c + 2{,}5092, \tag{4.1}$$

where V_c is cutting speed. The correlation $R^2 = 0{,}9594$.

Conclusion: it was defined, that as cutting speed increases the surface roughness increases.

Workpiece number 2. Surface roughness depending on current strength.

Table 4.3. Roughness measurement results

Surface number	**Current srength, A**	**Roughness, Ra I measurement results**	**Roughness, Ra II measurement results**	**Roughness, Ra III measurement results**	**Roughness, Ra Measurements average**
1	2	2,664	2,732	2,578	2,658
2	6	2,844	2,762	2,592	2,733
3	8	2,674	2,788	2,8	2,754
4	12	2,776	3,073	2,527	2,792
5	16	2,896	2,948	2,78	2,875

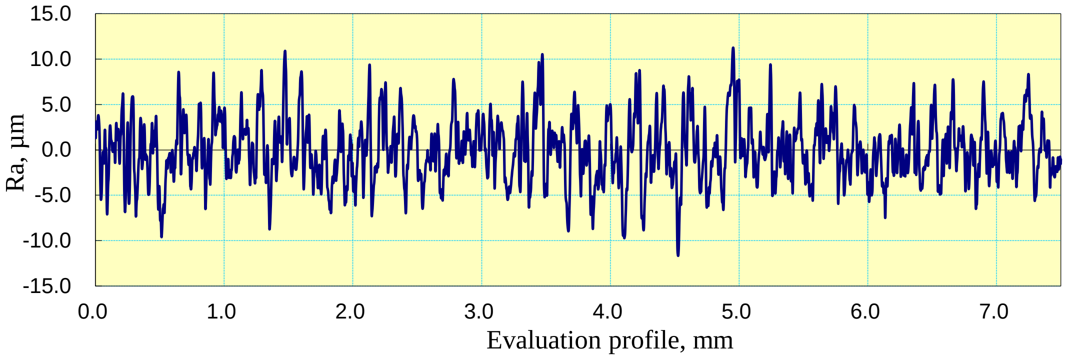


Fig. 4.21. Surface No. 1 evaluation profile graph

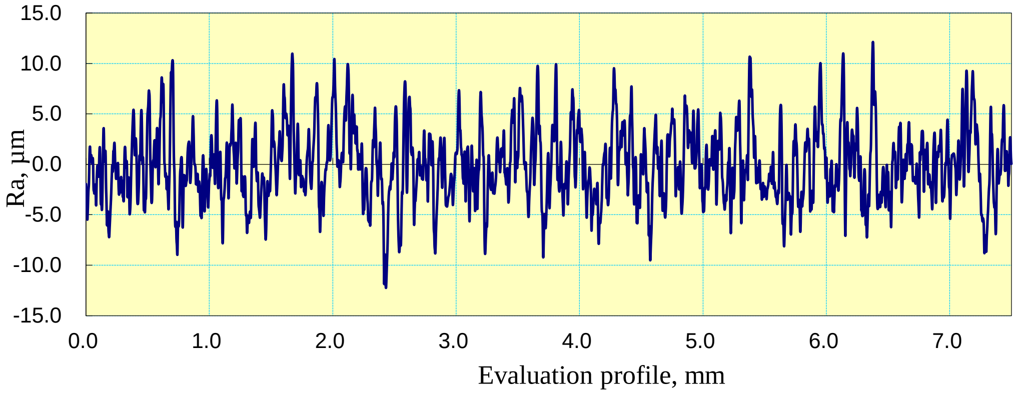


Fig. 4.22. Surface No. 2 evaluation profile graph

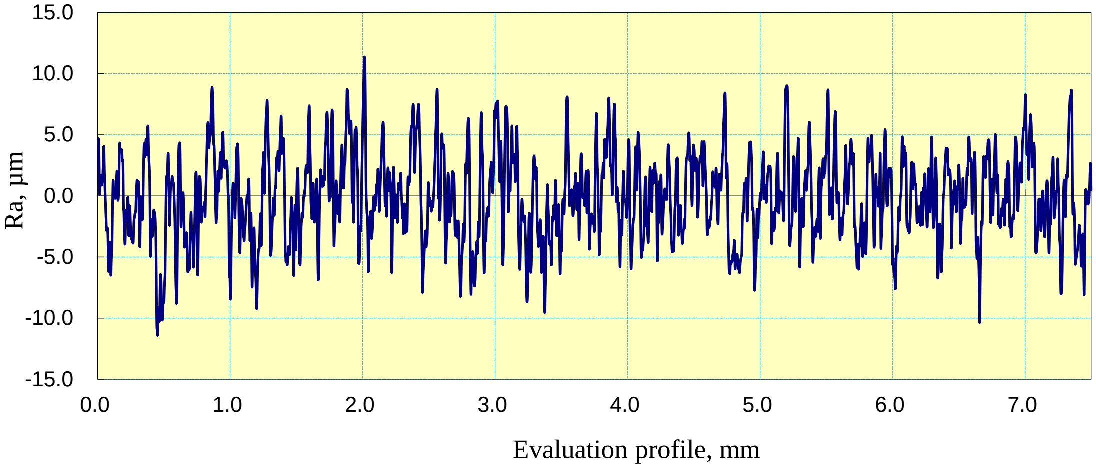


Fig. 4.23. Surface No. 3 evaluation profile graph

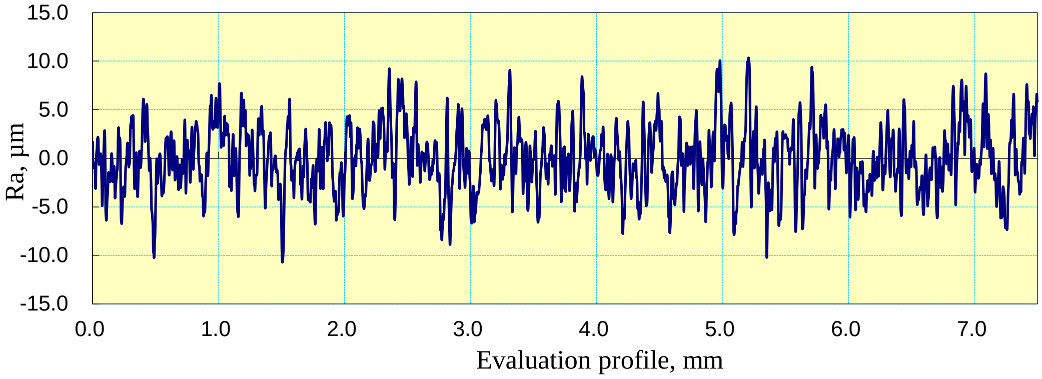


Fig. 4.24. Surface No. 4 evaluation profile graph

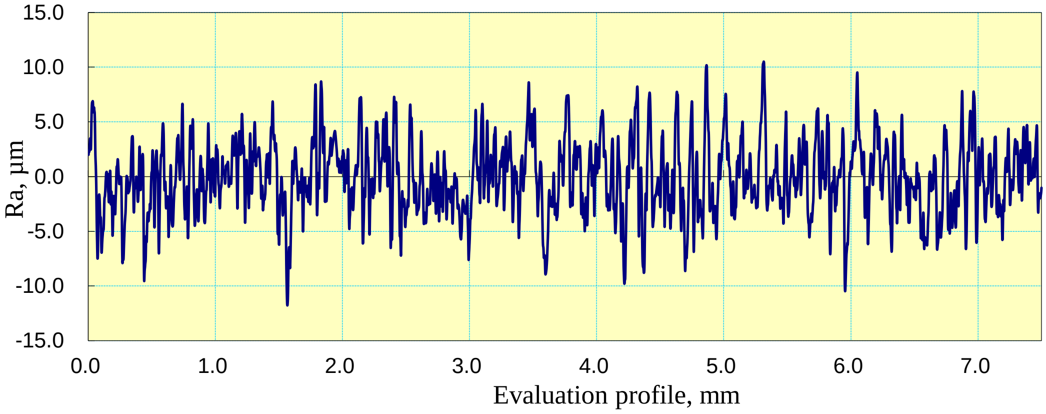


Fig. 4.25. Surface No. 5 evaluation profile graph

Later, there was drawn graph showing surface roughness dependence on current strength.

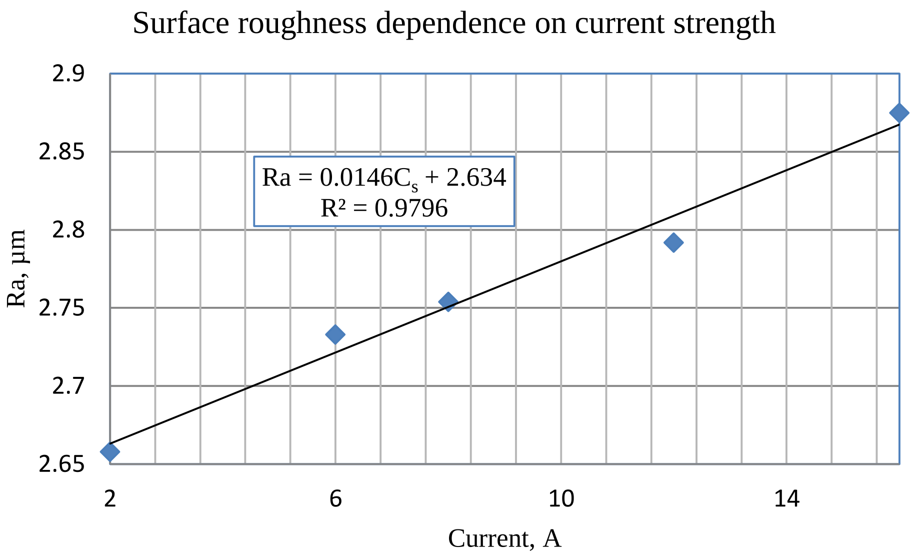


Fig. 4.26. Surface roughness dependence on current strength

It is seen from figure 4.26, that the surface roughness dependence on current strength is linear. The formula of linear dependence is:

$$Ra = 0{,}0146C_s + 2{,}634, \tag{4.2}$$

,where C_s is current strength. The correlation $R^2 = 0{,}9796$.

Conclusion: it was defined that as current strength increases, the surface roughness increases.

Workpiece number 3. Surface roughness depending on wire spinning speed.

Table 4.4. Roughness measurement results

Surface number	**Wire spinning speed, m/min**	**Roughness, Ra I measurement results**	**Roughness, Ra II measurement results**	**Roughness, Ra III measurement results**	**Roughness, Ra Measurements average**
1	5	2,765	2,763	2,634	2,721
2	7	2,834	2,726	2,897	2,819
3	9	2,845	2,923	2,651	2,806
4	11	2,822	3	2,852	2,891
5	13	3,421	3,428	3,349	3,399

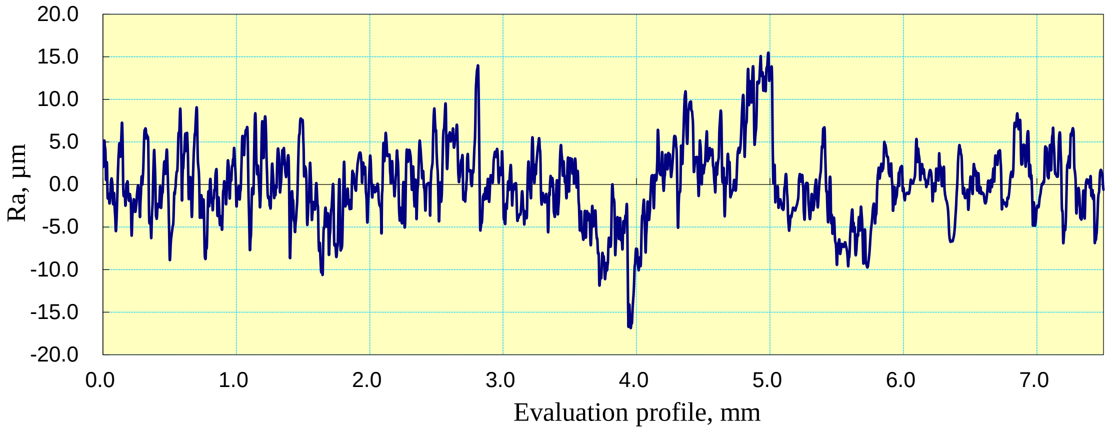


Fig. 4.27. Surface No. 1 evaluation profile graph

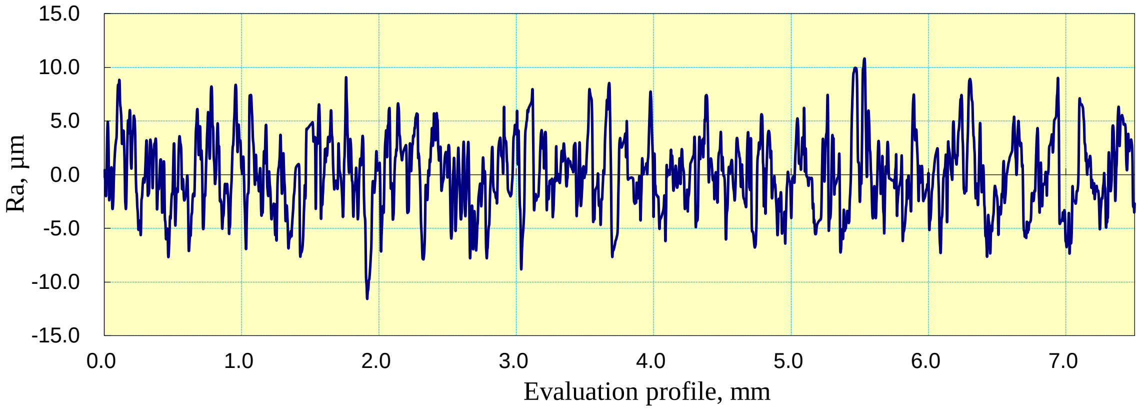


Fig. 4.28. Surface No. 2 evaluation profile graph

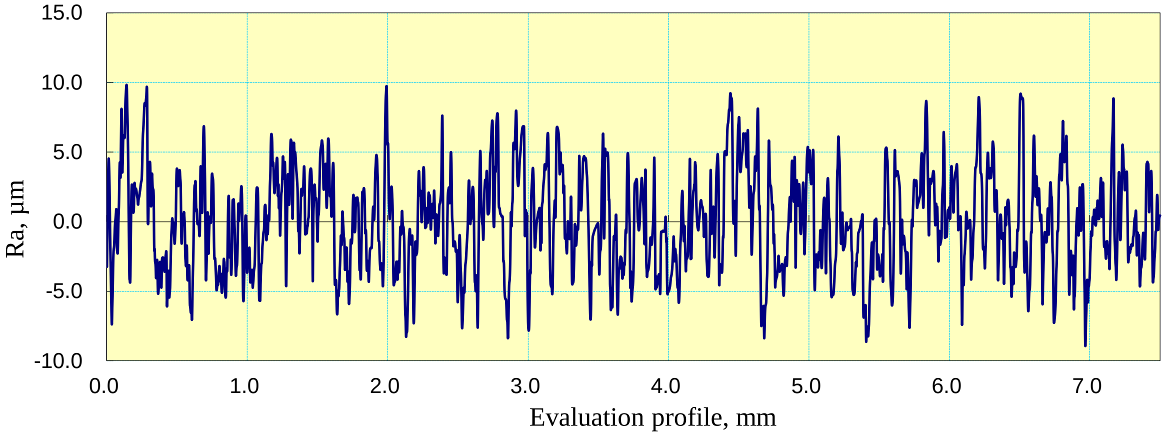


Fig. 4.29. Surface No. 3 evaluation profile graph

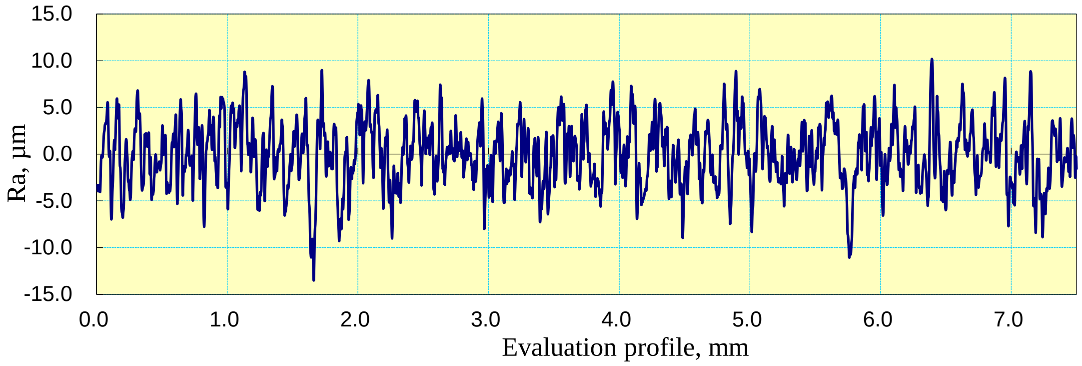


Fig. 4.30. Surface No. 4 evaluation profile graph

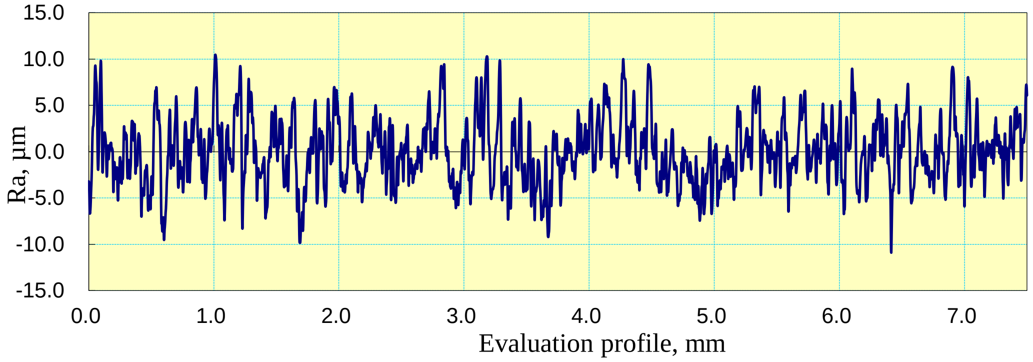


Fig. 4.31. Surface No. 5 evaluation profile graph

Later, there was drawn graph, showing surface roughness dependence on wire spinning speed.

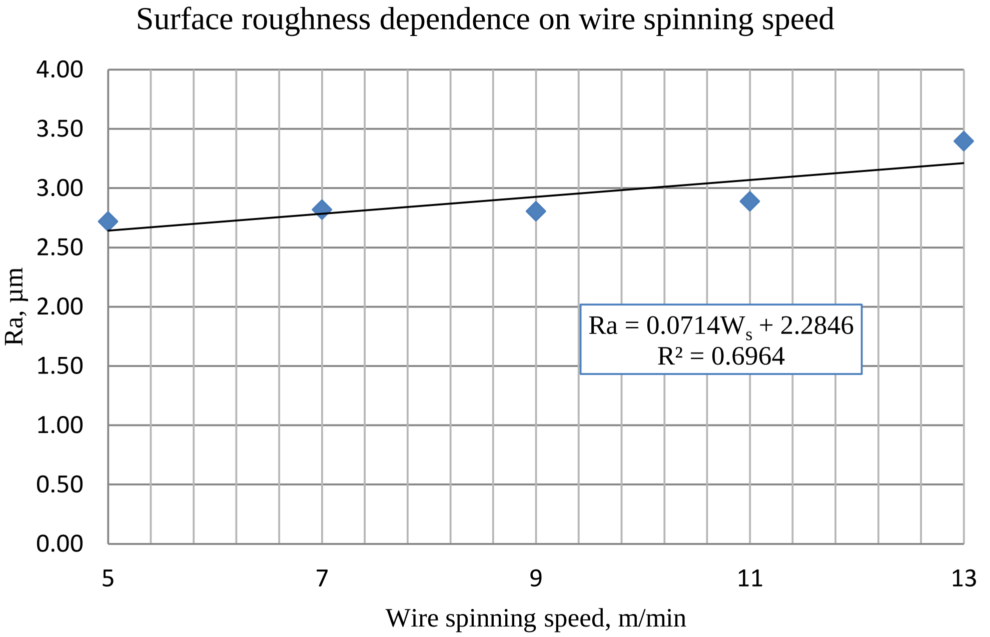


Fig. 4.32. Surface roughness dependence on wire spinning speed

It is seen from figure 4.32, that the surface roughness dependence on wire spinning speed is linear. The formula of linear dependence is:

$$Ra = 0{,}0714W_s + 2{,}2846, \tag{4.3}$$

where W_s is wire spinning speed. The correlation $R^2 = 0{,}6964$.

Conclusion: it was defined, that as wire spinning speed increases the surface roughness increases.

5. REGRESSION ANALYSIS

Using regression analysis there is set relationship between dependent variable – wire EDM parameters and independent variables factors *X*, which have impact to surface roughness.

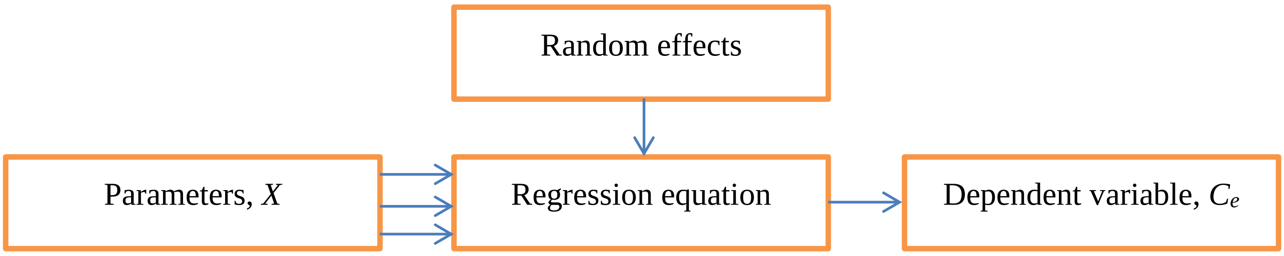


Fig. 5.1. Regression dependent variable C_e functional relationship with independent variables $X_1, X_2,\dots,X_k$

In most cases the real functional relationship is unknown and assessor has to choose the correct approximate function *f(X)*, which model is:

$$C_e = f(X) + e, \tag{5.1}$$

here *e* – random uncontrolled factors impact to surface roughness.

Regression analysis may solve these tasks:

1) essential factors x_i (i=1...k) and their changing diapazon setting;
2) model $C_e=f(X)$ selecting;
3) model $C_e=f(X)$ unknown parameters value setting;
4) model adequacy evaluation.

3 and 4 tasks are solved using computer software.

Choosing a key factors

If, for example, there is evaluated surface roughness so the parameters evaluating it are:

- cutting speed (V_c);
- current strength (C_s);
- wire spinning speed (W_s).

Choosing a model

Independent function *f(X)* in point X_0 environment, corresponding each factors average values can be expressed by gradual line section. If intervals of variation are not big, than there can be applied linear approach, which could be written like this:

$$f(X) = b_0 + b_i x_1 + b_2 x_2 + \cdots + b_i x_i + \cdots + b_k x_k, \tag{5.2}$$

here b_i – unknown parameters of model; i=0,1,...,k; x_i – factors creating set of X.

Later, there must be made table of stable and unstable parameters.

Table 5.1. Basic analysis data

Variable 1 Cutting speed m/min	**Variable 2 Current, A**	**Variable 3 Wire spinning speed m/min**	**Suurfase roughness Ra, μm**
1	16	10	2,655
2	16	10	2,704
3	16	10	2,831
4	16	10	2,914
5	16	10	3,104
3	**2**	10	2,658
3	**6**	10	2,733
3	**8**	10	2,754
3	**12**	10	2,792
3	**16**	10	2,875
3	16	**5**	2,721
3	16	**7**	2,819
3	16	**9**	2,806
3	16	**11**	2,891
3	16	**13**	3,399

Table 5.2. Regression coefficient values

b_0	b_1	b_2	b_3
1,666	0,111	0,019	0,061

From table 5.2 results there can be written surface roughness model like this:

$$Ra = 1{,}666 + 0{,}111V_c + 0{,}019C_s + 0{,}061W_s \tag{5.3}$$

Model significanse is varified from F – factor table, according to trustful interval level α=0,05 and degrees of freedom.

Table 5.3. Model significanse variance analysis (ANOVA)

Index	**df**	**SS**	**MS**	**F**
Regression	3	0,358	0,119	8,441
Residual	11	0,156	0,014	-
Total	14	0,514	-	-

It is seen, that calculated $F_{crit} = 3{,}59 < F_{cal} = 8{,}441$ so the choosen model is acceptable and can be used for surface roughness calculation.

Table 5.4. Regression statistics

Regression Statistics	
Multiple R	0,835
R Square	0,697
Adjusted R Square	0,615
Standard Error	0,119
Observations	15

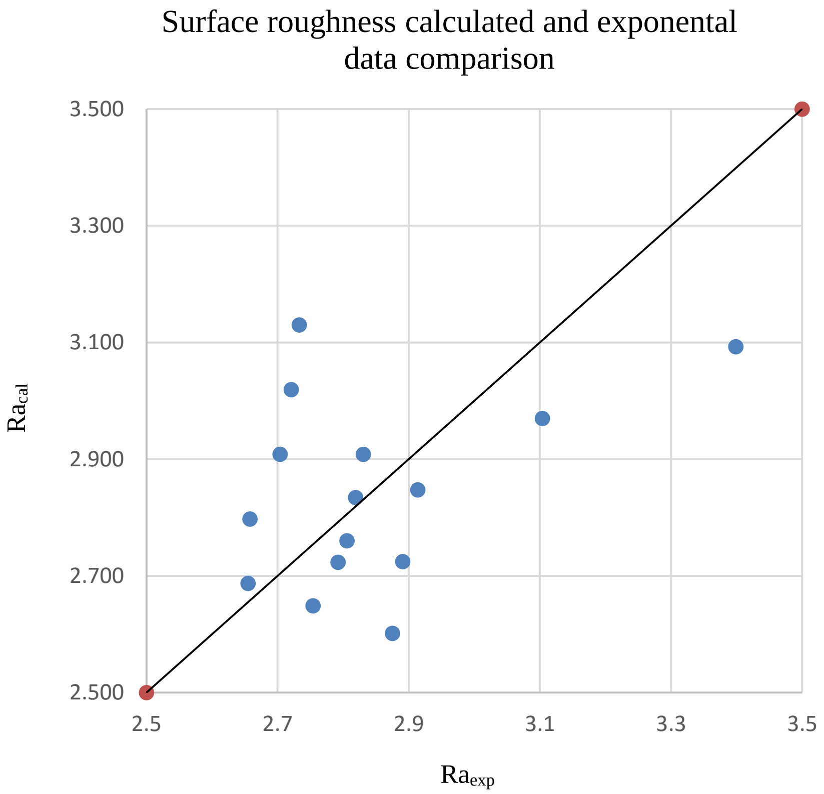


Fig. 5.2. Surface roughness calculated and exponental data comparison

Conclusion: regression analysis has showed, that the biggest impact of wire electrical discharge machining process parameters to surface roughness has cutting speed, in second place – wire spinning speed and the least impact to surface roughness has current strength.

CONCLUSIONS

1. Wire EDM experiment was carried out using wire EDM machine and Mitutoyo Surftest SJ-210 roughness measurement device. Using different brass wire with diameter of 0,5 mm there were cut wokpieces and were done surface roughness measurements depending on cutting speed, current strength and wire spinning speed.
2. Experimental surface roughness investigation has showed that cutting speed (V_c), current strength (C_s) and wire spinning speed (W_s) has significant influence on surface roughness.
3. It was defined, that as cutting speed increases the surface roughness also increases. With correlation coefficient R^2=0,9594 it could be approximated by linear dependence:
   $Ra = 0{,}1108V_c + 2{,}5092$.
4. There was investigated, that as current strength increases, the surface roughness increases. With correlation coefficient R^2=0,9796 it could be approximated by linear dependence:
   $Ra = 0{,}0146C_s + 2{,}634$.
5. It was defined, that as wire spinning speed increases the surface roughness increases. With correlation coefficient R^2=0,7 it could be approximated by linear dependence: $Ra=0{,}071W_s+2{,}28$.
6. In order to forecast surface roughness for different, in comparison, used process parameters, multivariable linear regression analysis was performed. It was defined, that with 95% probability (confidence interval a = 0,05), surface roughness could be predicted by linear regression model:
   $Ra = 1{,}666 + 0{,}111V_c + 0{,}019C_s + 0{,}061W_s$.
7. Model significanse was varified from F – factor table, according to trustful interval level α=0,05 and degrees of freedom. It was seen, that calculated $F_{crit} = 3{,}59 < F_{cal} = 8{,}441$ so the choosen model is acceptable and can be used for titanium alloy GR-5 surface roughness adequate evaluation.
8. Regression analysis has showed, that the biggest impact of wire electrical discharge machining process parameters to surface roughness has cutting speed, in second place – wire spinning speed and the least impact to surface roughness has current strength.

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