PROPOSAL TO USE WIRE ELECTRIC DISCHARGE MACHINING TO PREPARE TENSILE TESTING SAMPLES FOR AEROSPACE TITANIUM ALLOY TI-6AL-4V

Vlad Ciprian Cupşan[1] and Mihail Aurel Ţîţu[2, 3]
[1] Universal Alloy Corporation Europe, Baia Mare, Romania, vladcupsan@yahoo.com
[2] Lucian Blaga University of Sibiu, 10, Victoriei Street, Sibiu, Romania, mihail.titu@ulbsibiu.ro
[3] The Academy of Romanian Scientists, 54, Spitalul Independenţei, Sector 5, Bucharest, Romania

ABSTRACT: This paper presents the potential application of electrical discharge machining using wire on high hardness aerospace materials, such as titanium alloy Ti-6Al-4V annealed beta-extruded. The paper presents the general context of the current aerospace product requirements with relation to the machining of close tolerance samples for mechanical properties testing. It shows the general principle of wire electrical discharge machining (Wire EDM) as well as the equipment configurations available on the market. Details are provided related to aerospace materials, with emphasis on titanium alloy Ti-6Al-4V and the current requirements related to the material testing. In depth description of the tensile testing samples is given as an input to the proposed solution which applies the Wire EDM technology to the titanium alloy Ti-6Al-4V aerospace material in order to provide an improved solution to conventional machining.
KEYWORDS: electrical discharge machining, titanium alloy, Ti-6Al-4V, Wire EDM, tensile testing, aerospace.

1. INTRODUCTION

Currently the aerospace industry faces various difficulties, starting with the low demand due to sanitary crisis, as well as the fight on the technical and economic front. Keeping cost at a minimum, but at the same time improve the current design of the aircraft. By analysing, the aircraft structure, which consists in a large proportion of metallic materials, the rest being composite materials and other materials. The use of metallic materials in the structure of the aircraft makes it susceptible to corrosion, in some areas, where these materials are used and where the protection applied to the metallic materials is not resistant enough [1].

In order to avoid metallic material corrosion issue, the industry as approached the problem in two directions:

- Improving the current corrosion protection applied during the manufacturing processes, in order to increase the product life cycle to an acceptable level.
- Changing the materials used for some areas susceptible to corrosion, this being the “wet” areas of the aircraft (e.g. galley, lavatory).

One material which stands out from the other used for air frame structure manufacturing is the titanium alloy Ti-6Al-4V. This type of material has excellent corrosion resistance properties, in fact it does not require any corrosion protection by surface treatment. In some cases, paint is applied on parts manufactured from titanium alloy Ti-6Al-4V for aesthetic purposes.

The change to this new type of material must be balanced out from an economic point of view as cost for manufacturing the extrusion semi-finished product is ten times the cost of conventional aluminium. On the other side of the economic balance of this approach are the maintenance costs of the aircraft in service, which in case of severe corrosion issues of the aircraft can surpass the actual cost for switching to the titanium alloy parts in critical areas and on passenger floor structures.

One good example related to the direction that the industry is taking in order to solve this issue is the design of the Airbus A350 which features titanium alloy parts within the passenger floor structure in the area most susceptible to corrosion. The Airbus A350 galley and lavatory areas feature parts made from titanium alloy, especially longitudinal floor structure parts called Seat Rails.

The introduction of titanium alloys within the passenger floor structure has created a series of challenges for the production organizations in charge of delivering these parts.

Titanium alloy Ti-6Al-4V extrusion process is highly complicated due to the forces required to push the material through the die, but also the high temperature needed. All the above put a lot of strain on the equipment used.
Once the material has been rectified to comply with the straightness requirements it has to undergo a heat treatment step. In order to certify that the mechanical properties of the material are within the acceptable limits, tensile testing samples must be cut from the extruded material in order to perform the testing.

Manufacturing of the test samples adds a lot of costs to the product, as the very good mechanical properties of the titanium alloy material come against the mechanical processes normally used to cut the samples. Conventional machining requires a lot of effort to cut the sample section from the actual extrusion using usually band saws. Extrusion flange must be also cut using a band saw which requires a lot of time and cutting tools. All these efforts can be reduced by using the wire electrical discharge machining approach which allows the titanium material to be cut with less effort and tools.

2. WIRE ELECTRIC DISCHARGE MACHINING

2.1 Principle

This technological variant of electric discharge machining has had a rapid increase of usage ever since the first usage in 1969. The main area where this technology was and is currently used is the die manufacturing process, where the materials have high hardness and dimensional requirements have very tight tolerances.

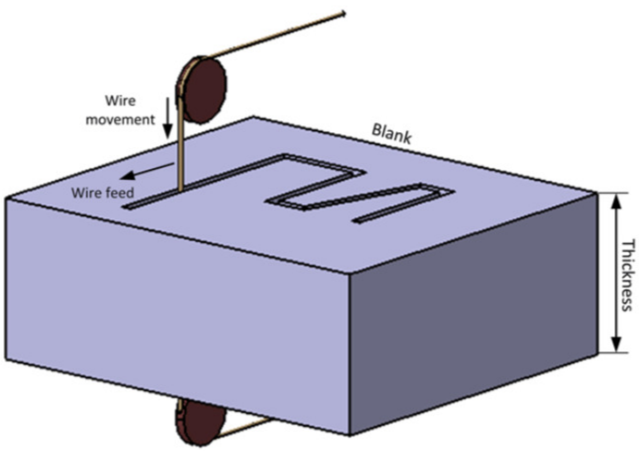

Figure 1. Representation of the wire electrical discharge principle [2]

The main difference between electric discharge using a solid electrode and wire electric discharge is the way that the surfaces are generated and the shape of the electrode used as a tool. Wire electrical discharge machining is characterized by the usage of tool electrode with the shape of a wire, with a high electrical conductivity which moves axially, being guided and tensioned between two support arms. The material to be cut is clamped so it allows the free movement of both support arms.

2.2 Process

During the machining process the wire electrode defines a straight line, at the level of a right segment described between the guides mounted between the support arms. The material to be machined is placed with relation to a plane which is parallel to the working table of the equipment. The straight line consists of the generating curve and the plane defines the directional curve, which follows the programmed movement of the wire electrode with relation to two directions which are mutually perpendicular to the same plane.

2.3 Equipment

The machining technological system defines in principle the same components as the machining system which used a solid electrode, this being the fame, the impulse generator, the circulation system of the dielectric fluid. But it also has some specific components such as: command system for the wire electrode movement, tensioning, guiding and running system of the wire electrode and operational management system for the process [3].

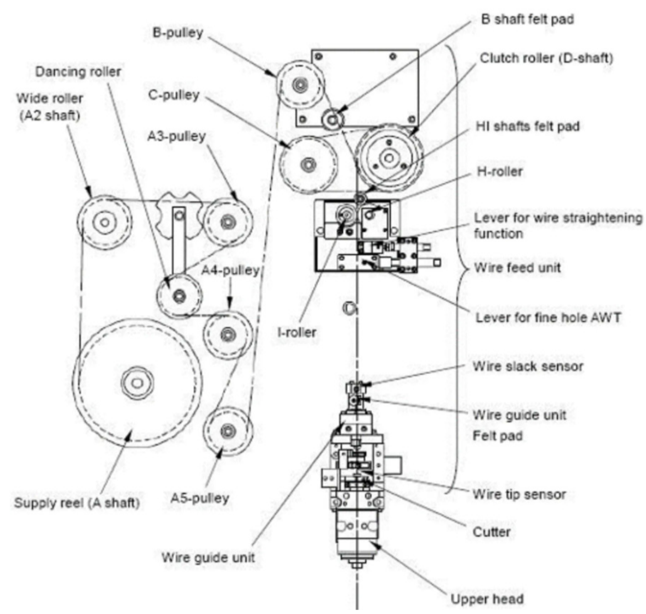

Figure 2. Wire electrical discharge equipment components [4]

It is required that this technological system maintain high execution precision and for the various dimensions of the semi-finished products, but also for long machining durations. Taking in consideration that usually these technological systems are continuously used for long durations, exceeding 100 hours per week.

In order to drive the system in all n axis, some high precision electromechanical variants are used, with guides and with rolling. The most frequently used electromechanical systems are the electrical step by step motors and reducers (with the role of adapting the execution sensibility needed to cope with the dynamic forces to which the drive systems are subjected). Command of the electrical motors is done via numerical control.

2.3.1 Impulse generators

Wire electrical discharge machining has some notable differences at the work area level compared to the solid electrode electrical discharge. Thus, the impulses applied in the interstice must be adapted to the following particularities:

- Cross-sectional area of the electrode is small, usually 0.005 to 0.07 mm^2, corresponding to diameters of 0.08 to 0.3 mm;
- Surface area in the processing phase is also small, usually 0.0025 to 2.5 mm^2;
- Small roughness required for the machined surface, with values Ra = 1 to 1.2 µm;
- Small thickness of the interstitial space (0.05 to 0.1 mm);
- The usage of water as dielectric fluid (deionized, demineralized).

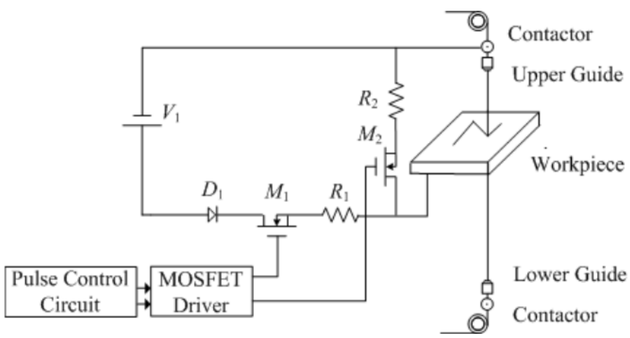

Figure 3. Pulse generator diagram [5]

Impulse generators used in equipment for wire electrical discharge machining are the ones with accumulation and relaxation command. The performance of this type of generators is below the commanded impulse generators, however these are still being used due to the active command to accumulate energy in condensers and the commanded relaxation of this energy in the interstice offers the possibility to control the electrical discharge parameters.

2.3.2 Wire electrode

The material used for the manufacturing of the wire electrodes must have good electrical conductivity properties and high thermo-physical properties. To these requirements we can identify additional requirements determined by the specific service conditions. All these properties are determined by the high mechanical resistance requirements:

- Required wire tensioning;
- Forces from the erosive process;
- Wire electrode as a precision tool;
- Permanent renewal of the active surface;
- Small dimensions of the erosive interstice.

To answer all these requirements the practice of wire electrical discharge machining has determined necessary the definition of standard electrodes. The wire electrodes used for electrical discharge machining have diameter between 0.03 mm and 0.3 mm, but currently diameters between 0.25 mm and 0.3 mm are used.

The material with the best properties for electrical discharge machining from which wire electrodes can be manufactured is electrolytic copper, with very good thermo-physical properties and high electrical conductivity.

Figure 4. EMD wire visible prior to material cutting [4]

A direction with good results related to the manufacturing of wire electrodes are represented by the layered manufacturing technologies. Wire electrodes being made from a core with high mechanical properties, in general steel or brass and concentrically positioned layers made from materials with good thermo-physical and electrical properties.

The usage of wire electrodes made from brass with layers of zinc have led up to good process stability and high productivity compared to the usage of non-layered wire electrodes.

2.3.3 Configurations available on the market

The wire EDM machine Agie-Charmilles Cut E 350 from GF Machining Solutions recently replaced a machine from the 1990s at Niessing. The first advantages can be seen with the naked eye: The new one takes up less space. In addition, their “Econowatt module” stand-by mode is designed to save energy. The integrated collision protection protects both the workpiece and the machine from damage.

Figure 5. EDM machine Agie-Charmilles Cut E 350 from GF Machining Solutions [6]

With the Agie-Charmilles Cut E 350, spark erosion-cutting out of the ring is economical and extremely material-saving. Especially for gold and platinum, Niessing wants to keep material loss as low as possible, so special filter cartridges catch up on the precious material loss. The wire EDM machine receives the contour directly as an NC program from the CAM system. The sophisticated Agie-Charmilles spark erosion technology, in conjunction with the new, efficient IPG generator, enables precise machining.

Makino revised its wire erosion machine UP6. The problem of thermal expansion was solved by flushing with an evenly tempered dielectric. Also, the X-axis now moves without disturbances. This is due to the continuous cleaning of the sliding plates of the tank seal via a water curtain. According to Makino, extra-long roller guides for maximum precision reduce vibration and further improve the rigidity of the machine. The recirculating ball drives, which are protected from dirt by a complete cover, are intended to extend the service life. Makino has also redeveloped the wire running system. Here, improved contour fidelity for inner and outer radii ensure more reliable wire threading for demanding geometries and small start bores. To improve wire threading, the wire threading system has also been equipped to operate either dry or with water jet.

Figure 6. Makino wire erosion machine UP6 [6]

The Spanish company ONA EDM presented an eroding machine developed for the manufacture of large wheels for the turbine industry. With the wire erosion machine AV100, the newly developed generator at the heart of the system enables fine machining with a surface quality of up to Ra = 0.1 µm. The CNC with a 23" touch screen controls up to eight axes, seven of them simultaneously.

Figure 7. ONA EDM wire erosion machine AV100 [6]

The ONA AV cuts a wire of 0.33 mm in diameter at 450 mm2/min. According to the manufacturer, the ONA Easycut digital generator performs a cut without electrolytic corrosion risk, without speed limitation and with complete surface integrity of the cut material. In addition, the Aqua-Prima filter system does not require replaceable filter cartridges.

3. AEROSPACE MATERIALS AND COMPONENTS

3.1 Ti-6Al-4V annealed beta-extruded

This titanium alloy is considered the main material due to its mechanical and corrosion resistance properties, which allows for wide application within the aerospace industry. Ti-6AL-4V alloy has a good strength to weight ratio, compared to steels and nickel-based alloys.

Titanium, in general, and specifically titanium alloy Ti-6AL-4V are known for other applications outside the aerospace industry, most importantly within the medical sector, with a wide use for implantation in the human body to substitute bones. The properties which make it suitable for medical application are its exceptional mechanical properties, thin oxide layer, small elastic modulus and most importantly its low density.

Physical Properties	Titanium – Ti6Al-4V
Chemical composition (%)	Al (6.0), V (4.0), C (0.08), N (0.05), O (0.2), H (0.0125), Fe (0.3), Ti (remaining)
Density ($kg\,m^{-3}$)	4429
Hardness (BHN)	334
Ultimate Tensile Strength (MPa)	950
Modulus of Elasticity (GPa)	113.8
Poisson's Ratio	0.34
Shear Modulus (GPa)	44
Specific Heat Capacity ($J\,(g\,°C)^{-1}$)	0.526
Thermal Conductivity ($W\,(m\,K)^{-1}$)	6.7
Melting Point (°C)	1604–1660

Figure 8. Titanium alloy Ti-6Al-4V composition and physical properties [2]

The same properties have made this material the best option when it comes to aerostructures, mainly it qualified for aerospace application due to its strength to weight ratio which allows the substitution of aluminium alloy parts with titanium alloy parts without adding significant weight to the aircraft.

Its exceptional mechanical properties exceed the ones from aluminium alloys, thus allowing smaller thicknesses for aerostructure parts, which in term reduces even more the weight of the aircraft.

The property which makes the titanium alloy more suitable for aerospace application compared to conventional aluminium alloys is the corrosion resistance property. This titanium alloy property makes it the best choice for aerostructures especially for the passenger floor grid.

3.2 Aircraft passenger floor grid

In general, the aircraft passenger floor grid is composed of the following components:

- Crossbeams, which carry most of the weight of the passengers and are fixed to the frames of the fuselage barrel section. Crossbeams are usually made from conventional aluminium alloys or from aluminium-lithium alloys.
- Seat rails are parts which are assembled on the longitudinal axis of the aircraft with an angle of 90 degrees from the crossbeams. Seat rails are the only components of the passenger floor grid which are visible in the cabin. This makes the parts susceptible to mechanical shocks and contact with various fluids.
- Struts, which are positioned on the z-axis of the aircraft and are fixed to the crossbeams and the frames of the fuselage barrel section.
- Fittings are parts which allow the construction of floor grid as a standalone component prior to integration with the fuselage barrel section of the aircraft.
- Small parts, which are in general made from aluminium alloy thin sheet metal and which typically are formed. The small parts are fixed to the main components of the passenger floor grid and allow the installation of the various aircraft systems.

The above present in general the benefits of using titanium alloys for aerostructure components, but there are a series of disadvantages which are linked with the high price of the titanium component price. Main contributing factors to the price of the titanium components are:

- High costs of titanium raw material;
- Costs for processing the titanium billet into titanium extrusion;

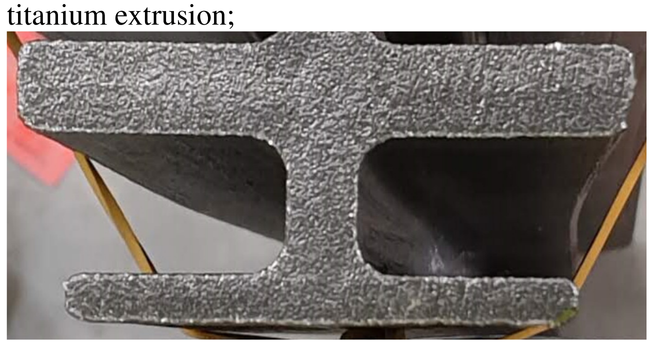

Figure 9. Titanium alloy Ti-6Al-4V extrusion

- High costs of quality control testing, with a big contribution from the sample preparation step.
- Added costs of machining the extrusion into the required component.

This paper focuses on the reduction of the costs for quality control testing, by converging towards titanium alloy sample preparation for tensile testing.

3.3 Tensile testing sample requirements

As described by the aerospace applicable standard BS EN 2002-1 with the title “Metallic materials – Test methods” in Part 1 “Tensile testing at ambient temperature” clear definition of the tensile testing sample requirements is given.

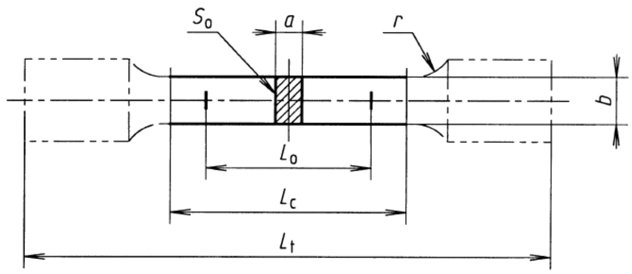

Figure 10. Machined test piece of rectangular cross-section [7]

Where:

- a is the test piece thickness;
- b is the test piece width;
- r is the test piece transition radius;
- S_0 is the original cross-sectional area;
- L_0 is the original gauge length;
- L_c is the parallel length;
- L_t is the test piece length.

Generally, the test piece has gripped ends, which are wider than the width (b) of the parallel length. The width of these ends shall be at least 20 mm and not more than 40 mm. The parallel length (Lc) shall be connected to the ends by means of transition curves with a radius (r) of at least 12 mm [7].

4. PROPOSED APPLICATION

Taking in consideration the big difference between the titanium extrusion cross-section and the tensile testing sample cross-section, with conventional machining and correlated with the hardness of the material, it can take multiple hours to prepare the tensile testing sample. This leads to increased costs due to the multiple setups required in order to remove the excess material. In general, a band saw is used to perform the coarse material removal and a CNC machine is required to manufacture the contour and surface of the tensile testing sample. All the above requiring a lot of resources such as equipment, clamping tooling, cutting tools.

A much easier approach would be to use a wire EDM machine to extract the tensile testing sample with less resources required. This application of wire EDM can be performed in two setups on the wire EDM machine:

- Setup 1, by performing the wire EDM cutting with the extrusion material clamped parallel to the wire electrode.
- Setup 2 would be applied to manufacture the required contour of the tensile testing sample, by positioning the rectangular pieces extracted in setup 1, parallel to the machine working table.

5. CONCLUSIONS

Wire electrical discharge machining presents multiple advantages when applied for the manufacturing of the tensile testing sample for titanium alloy Ti-6Al-4V annealed beta-extruded, compared to conventional machining.

One main advantage is the reduced resources needed to perform the machining operations, regarding clamping tooling and cutting tools. Also due to the reduced number of setups required, two per the above proposed application, a significant reduction in time is possible.

Another important advantage of using wire EDM to manufacture the tensile testing is the quality of the machined results, compared to the conventional machining where rework of surfaces is often required in order to comply with the requirements.

6. REFERENCES

1. Cupșan V.C., Țîțu M.A. and Pop G.I., *The influence of sulfuric acid anodizing electrochemical process on surface treatment adhesion*, Nonconventional Technologies Review, (2018).
2. Wasif, M., Iqbal, S. A., Fatima, A., Yaqoob, S., and Tufail, M., *Experimental investigation for the effects of wire EDM process parameters over the tapered cross-sectional workpieces of titanium alloys (Ti6Al-4V)*, Mech. Sci., 2020.
3. Nanu A. and Nanu D., *Prelucrarea prin eroziune electrică*, Tratat de tehnologii neconventionale, 2004.
4. Ian Wright, *EDM 101: Electrical Discharge Machining Basics*, www.engineering.com, 2017.
5. Mu-Tian Yan, Tsung-Chien Lin, *Development of a Pulse Generator for Rough Cutting of Oil-based Micro Wire-EDM,* 18th CIRP Conference, 2016.
6. Simone Käfer, *Three wire EDM machines in comparison,* www.etmm-online.com, 2018.
7. BS EN 2002-1, *Metallic materials – Test methods, Part 1: Tensile testing at ambient temperature,* British standard aerospace series, 2005.