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A contribution on the modelling of wire electrical discharge machining of a γ-TiAl alloy

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Abstract

Wire electrical discharge machining (WEDM) is a manufacturing process suitable for high-precision cutting of complex and irregular shapes through difficult-to-machine electrically conductive components. In recent years, wire EDM has become a key non-traditional machining process, widely used in the aerospace and automotive industry. Although this technology has been broadly investigated, literature is still limited on the use of wire EDM for intermetallic alloys, and the applications on gamma titanium aluminides are rather unexplored. Such materials are attracting considerable interest due to the outstanding combination of properties, and they have proved to be eligible for thermo-mechanically stressed parts of aeroengines. Nevertheless, the poor machinability of gamma titanium aluminides has been reported in conventional (i.e. turning, milling, and drilling) and non-conventional machining, such as ECM. Further, machinability results strictly depend on the chemical composition of the specific alloy. This paper investigates the interactions between common process parameters of WEDM and final quality of the generated surface, through analysis of variance (ANOVA) and regression models based on experimental results. In particular, the paper is focused on the effects of pulse on time, pulse off time, servo-reference voltage, and wire tension on the surface finish during the WEDM of a Ti-48Al-2Cr-2Nb (at. %) γ-TiAl alloy. Results are discussed and compared with reference to the models available in literature.

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Keywords: Wire EDM; Modelling; Gamma titanium aluminide.

1. Introduction

Aerospace and automotive industries have to meet the severe environmental regulations aimed to the minimization of fuel consumption, resource wastes, and emissions. When considering the life cycle assessment of complex products as vehicles and aircrafts, the weight reduction and the increase of engines’ thermal efficiency were identified as irreplaceable strategies for the use phase optimization. From this need, the use of advanced materials (as Al- or Ti-based lightweight alloys, composites, and Ni-based heat-resistant superalloys) has been arising over the last decades.

Since 1980s, TiAl alloys have been the subject of a constant scientific investigation, due to the specific properties that make them eligible to replace denser Ni- or Fe-based alloys currently in use in the aerospace industry, as well as for the application in turbines, car valves or turbochargers [1].

With respect to standardly used alloys, the advantages of titanium aluminides can be traced back to the low density and the good oxidation behaviour resulting by the high aluminium content, the high melting point due to the stable ordered structure, the thermal stability, the small sensitivity to structural coarsening, the good creep properties (particularly in a selected temperature range, and mainly for creep rupture).

These alloys are emerging as a potential material for high-temperature and mechanical stressed applications under chemically aggressive environments, but they still have a limited distribution because of their poor machinability, which has been highlighted both in conventional (i.e. milling, turning, drilling) [2-5] and non-conventional machining (as EDM [6] and ECM [7]). When compared to common Ti-based aerospace alloys (e.g. Ti-6Al-4V), the mechanical properties of titanium aluminides show significantly higher brittleness (fracture toughness 50% lower, and elongation 80% lower) at

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room temperature. In addition, many other factors emphasize the tendency to rapidly wear the cutting edges, as the presence of abrasive particles (i.e. titanium di-borides) in the alloys' microstructure, the sensitivity to strain rate, the saw-tooth chip shape, and the built-up edge [8, 9]. The low thermal conductivity leads to an excessive generation of heat in the cutting zone, resulting in high cutting temperatures [10]. Historically, the quality of machined surfaces is a critical issue for aerospace components [11], and the achievement of a good surface integrity provides many opportunities to avoid failures, enhance component integrity, and reduce overall costs [12].

In recent years, wire electrical discharge machining has been significantly improved to satisfy the strict technological requirements in various manufacturing fields, and particularly in the precision die industry. WEDM is a manufacturing system applicable to different materials, like metallic composites and intermetallic alloys. By using WEDM it is possible to cut materials which are difficult-to-machine under conventional machining approaches. The material is eroded by series of discrete sparks between the workpiece and a tool electrode (wire) immersed in a liquid dielectric medium (as deionized water). These electrical discharges melt and vaporize small amounts of workpiece material, which are then ejected and flushed away by the dielectric. Since workpiece and electrode do not have any mechanical contact, conductive material can be machined by WEDM, regardless of their hardness and toughness. For such reasons, this technology has become an important non-conventional machining process, widely used in the aerospace and automotive industries. Other applications of wire EDM include the fabrication of tools and dies for stamping and extrusion, fixtures and gauges, prototypes, medical parts, and grinding wheel form tools. Furthermore, the high degree of accuracy and the fine resultant surface finish make WEDM a valuable process [13]. As a result of the large number of process variables and complex stochastic process mechanisms, the selection of optimum machining parameter combinations for obtaining higher accuracy is a challenging task in WEDM. Researchers investigated various aspects of the EDM process, optimizing the process variables, improving the performance measures, simplifying the electrode design and manufacture, monitoring and controlling the sparking process and the surface quality improvements. Recently, wire EDM was used to machine a wide variety of miniature and micro-parts from metals, alloys, sintered materials, cemented carbides, ceramics and silicon [14-16].

Literature still lacks about the use of EDM for machining intermetallic alloys such as TiAl. Sinking-EDM in γ-TiAl alloys was experimentally studied by Klocke et al. [17], whilst Sarkar et al. analyzed the wire EDM of gamma titanium aluminide alloys focusing on modelling and process parameter optimization [18-20]. Moreover, many different alloys belonging to the γ-TiAl group are available. Slight differences in chemical composition, as well as the thermal treatments, influence the microstructures and the mechanical/thermal properties. The selection of optimum process parameters must be carefully evaluated for each alloy, to reach a satisfactory compromise in terms of process effectiveness and surface quality [21]. This paper investigates the possible interactions between common process parameters of wire EDM and final quality process measurements through Design of Experiments (DoE) and Analysis of Variance (ANOVA).

2. Experimental set-up and measurements

An experimental campaign was carried out on a Ti-48Al-2Cr-2Nb gamma titanium aluminide (γ-TiAl) ingot by means of a wire electrical discharge machine. The chemical composition of the alloy is reported in Table 1, in weight percentage. The workpiece was melted two times in a vacuum arc furnace. It had an initial conical shape, needed to allow the extraction of the ingot from the mold, with diameter ranging approximately from 160 to 150 mm. Prior to wire EDM cuts, the bar was turned to obtain a constant diameter of 140 mm, and to eliminate the external crust due to the melting process.

Table 1. Gamma-TiAl chemical composition.

Element	Ti	Al	Nb	Cr
Weight percentage	60.30	32.10	4.85	2.47

Wire EDM tests were run by using a brass wire of 0.25 mm in diameter, and deionized water as dielectric fluid. Starting from the bar, the cuts were performed with the aim to obtain disks with a thickness of 10 mm. In order to determine influential parameters for wire EDM, tests have been executed by using the Design of Experiment (DoE) approach. An experimental plan of 2^4 has been chosen in order to have representative data. According to Montgomery [22], as the number of factors increases, the number of effects that can be estimated also increases. A 2^4 experiment has 4 main effects, 6 two-factor interactions, 4 three-factor interactions, and 1 four-factor interaction. Pulse on time (T_{on}), pulse off time (T_{off}), servo-reference voltage (SV) and wire tension (WT) have been adopted as factors. Table 2 details the four different wire EDM process variables and their levels. The other parameters have been kept constant to ensure a proper comparison between the tests (peak current = 10 A, wire feed = 6 m/min). The selection of process parameters was carried out with respect to the machine tool in use, and taking into account the existing literature [18-20].

Table 2. Factors and factor levels.

Factor	Low (-1)	High (+1)
Pulse on time, T_{on} (0.1× μs)	6	10
Pulse off time, T_{off} (μs)	9	15
Servo-reference voltage, SV (V)	45	55
Wire tension, WT (N)	10	14

Focusing on the applications of TiAl intermetallics, surface morphology is a key aspect to be assessed. After the wire EDM cuts, the disks were cleaned with acetone to remove residual particles, and a Form Talysurf 120 profilometer was used to evaluate quantitatively the surface roughness of the WEDMed surface, in a direction perpendicular to the feed. The set of 2D surface roughness parameters included the mean average R_{a}, the average maximum height of the profile

R_t and the skewness R_{sk}. The length of measures was equal to 2.4 mm, and the cut-off length was set to 0.8 mm. Three repetitions were considered for each test. Results were analysed by using the Minitab statistical software. In order to better investigate the characteristics of the process in terms of surface morphology, 3D roughness measurements were also carried out on areas of approx. 2 mm × 2 mm (Figure 1).

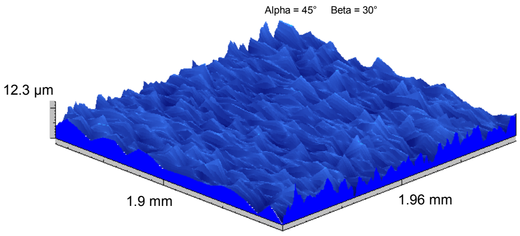

Fig. 1. 3D topographic map for T_{on} : -1, T_{off} : -1, SV : -1, and WT : +1.

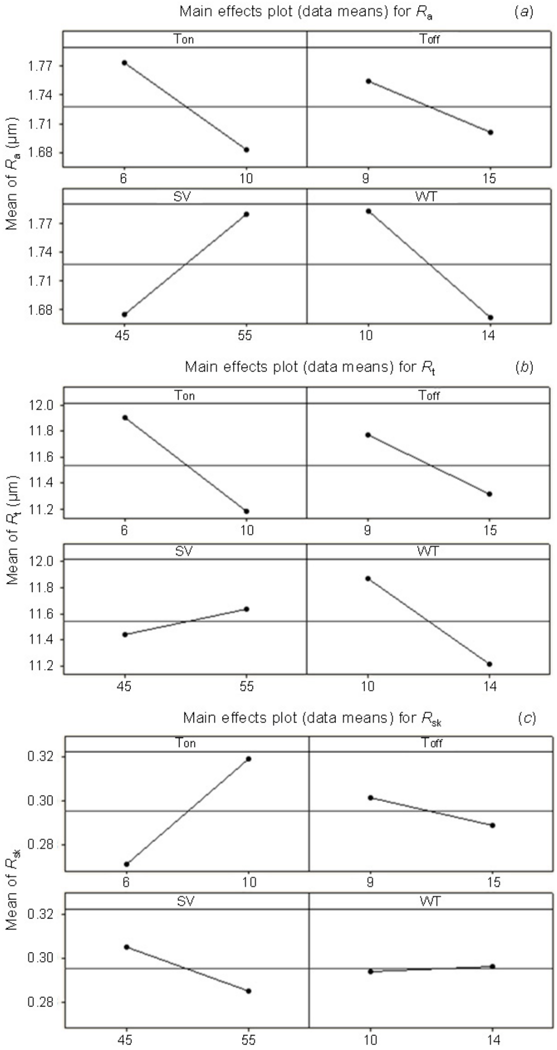

Fig. 2. Effects of factors on R_a (*a*), R_t (*b*), and R_{sk} (*c*).

Moreover, machined surfaces were observed by a scanning electron microscope LEO 1450 VP, equipped with an energy dispersive spectrograph (EDS) microprobe for semi-quantitative elemental analysis. An Emcotest M4U 025 universal tester was used to evaluate WEDMed surface hardness, according to HRB test specification. $HV_{0.2}$ micro-hardness profiles at different radial positions along disk cross-sections were obtained by a semiautomatic micro-durometer Leica VMHT, equipped with Vickers indenter.

3. Data analysis and discussion

In order to analyse the results of the experimental design, analysis of variance (ANOVA) was performed. Figures 2 and 3 show the main effects and the interaction plots for all the factors. These plots are useful tools for an assessment of the effects of factors on the responses. For all the roughness indices, analysis of variance results are listed in Tables 3, 4, and 5.

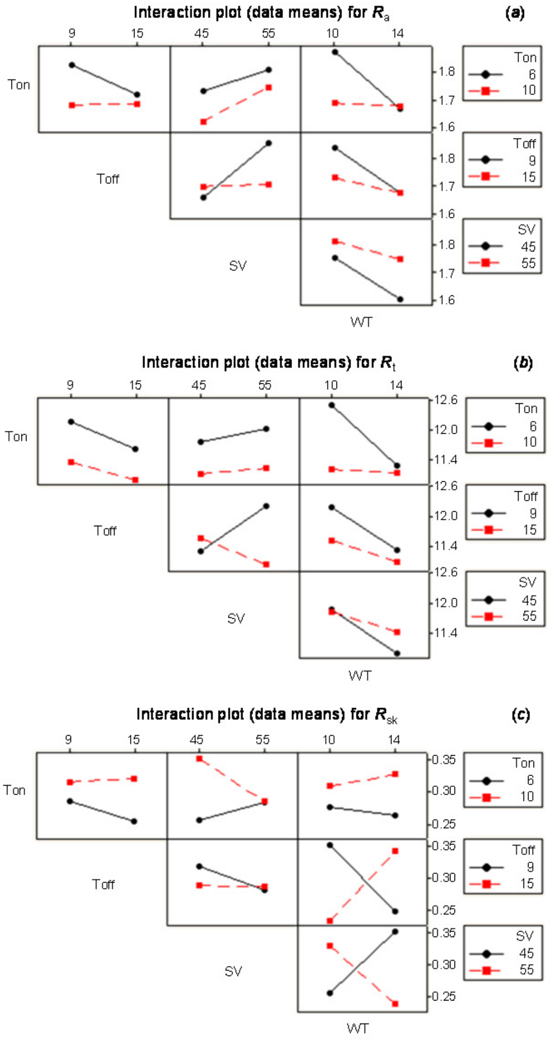

Fig. 3. Interaction effects of factors on R_a (*a*), R_t (*b*), and R_{sk} (*c*).

Table 3. Analysis of variance for R_a ($R^2 = 77.6$ %, $R^2_{adj} = 68.2$ %).

Source	DF	SS	MS	F	p
Main Effects	4	0.4108	0.1027	8.18	< 0.001
T_{on}	1	0.0988	0.0988	7.87	0.008
T_{off}	1	0.0339	0.0339	2.70	0.110
SV	1	0.1313	0.1313	10.45	0.003
WT	1	0.1467	0.1467	11.68	0.002
2-Way Interactions	6	0.3306	0.0551	4.39	0.002
$T_{on} \cdot T_{off}$	1	0.0384	0.0384	3.05	0.090
$T_{on} \cdot$ SV	1	0.0074	0.0074	0.59	0.450
$T_{on} \cdot$ WT	1	0.1194	0.1194	9.50	0.004
$T_{off} \cdot$ SV	1	0.1089	0.1089	8.67	0.006
$T_{off} \cdot$ WT	1	0.0360	0.0360	2.87	0.100
SV · WT	1	0.0207	0.0207	1.65	0.209
3-Way Interactions	4	0.6975	0.1743	13.88	< 0.001
$T_{on} \cdot T_{off} \cdot$ SV	1	0.4952	0.4952	39.43	< 0.001
$T_{on} \cdot T_{off} \cdot$ WT	1	0.0555	0.0555	4.42	0.043
$T_{on} \cdot$ SV · WT	1	0.0525	0.0525	4.18	0.049
$T_{off} \cdot$ SV · WT	1	0.0943	0.0943	7.50	0.010
Residual Error	33	0.4145	0.0126		
Total	47	1.8534			

Table 4. Analysis of variance for R_t ($R^2 = 75.9$ %, $R^2_{adj} = 65.6$ %).

Source	DF	SS	MS	F	p
Main Effects	4	14.34	3.59	6.49	0.001
T_{on}	1	6.28	6.28	11.37	0.002
T_{off}	1	2.47	2.47	4.47	0.042
SV	1	0.45	0.45	0.81	0.375
WT	1	5.15	5.15	9.33	0.004
2-Way Interactions	6	11.84	1.97	3.57	0.008
$T_{on} \cdot T_{off}$	1	0.11	0.11	0.19	0.664
$T_{on} \cdot$ SV	1	0.08	0.08	0.15	0.703
$T_{on} \cdot$ WT	1	4.13	4.13	7.48	0.010
$T_{off} \cdot$ SV	1	6.18	6.18	11.18	0.002
$T_{off} \cdot$ WT	1	0.64	0.64	1.16	0.289
SV · WT	1	0.71	0.71	1.29	0.265
3-Way Interactions	4	31.10	7.77	14.08	< 0.001
$T_{on} \cdot T_{off} \cdot$ SV	1	25.92	25.92	46.94	< 0.001
$T_{on} \cdot T_{off} \cdot$ WT	1	2.99	2.99	5.42	0.026
$T_{on} \cdot$ SV · WT	1	0.49	0.49	0.89	0.352
$T_{off} \cdot$ SV · WT	1	1.70	1.70	3.07	0.089
Residual Error	33	18.22	0.55		
Total	47	75.50			

All the terms up to the three-way interactions were fitted in the complete model. Analysis of results leads to the conclusion that, even if variations of measured roughness indices are small, the factors T_{on}, SV and WT show significant effect on R_a. In particular, lower levels of T_{on} and WT give maximum R_a roughness. While, on the contrary, the lowest value of SV gives the minimum R_a. It is also important to underline, as shown in Figure 3 and in Table 3, that interactions between factors can not be neglected.

Table 5. Analysis of variance for R_{sk} ($R^2 = 66.0$ %, $R^2_{adj} = 51.6$ %).

Source	DF	SS	MS	F	p
Main Effects	4	0.0348	0.0087	1.46	0.235
T_{on}	1	0.0280	0.0280	4.72	0.037
T_{off}	1	0.0019	0.0019	0.32	0.575
SV	1	0.0048	0.0048	0.80	0.377
WT	1	0.0001	0.0001	0.01	0.915
2-Way Interactions	6	0.2815	0.0469	7.91	< 0.001
$T_{on} \cdot T_{off}$	1	0.0040	0.0040	0.68	0.415
$T_{on} \cdot$ SV	1	0.0268	0.0268	4.52	0.041
$T_{on} \cdot$ WT	1	0.0031	0.0031	0.53	0.471
$T_{off} \cdot$ SV	1	0.0041	0.0041	0.69	0.412
$T_{off} \cdot$ WT	1	0.1378	0.1378	23.23	< 0.001
SV · WT	1	0.1055	0.1055	17.79	< 0.001
3-Way Interactions	4	0.0645	0.0161	2.72	0.046
$T_{on} \cdot T_{off} \cdot$ SV	1	0.0484	0.0484	8.16	0.007
$T_{on} \cdot T_{off} \cdot$ WT	1	0.0013	0.0013	0.23	0.638
$T_{on} \cdot$ SV · WT	1	0.0001	0.0001	0.01	0.909
$T_{off} \cdot$ SV · WT	1	0.0147	0.0147	2.47	0.126
Residual Error	33	0.1958	0.0059		
Total	47	0.5765			

Residual plots (in Figure 4, for R_a) confirm that there is no severe departure from normality. Concerning R_t (Figure 2*b* and 3*b*), all the factors are significant, except for SV. However, significant interactions between SV and T_{off}, and between T_{on} and WT were observed. Lower values of T_{on}, T_{off} and WT give the highest R_t roughness. Moreover, as far as the skewness is concerned, T_{on} results to be the most important factor among all. In addition, also for this case, the interactions between factors have to be considered. It is worth pointing out that optimization of parameters for R_a, R_t and R_{sk} seems to be a difficult goal to reach.

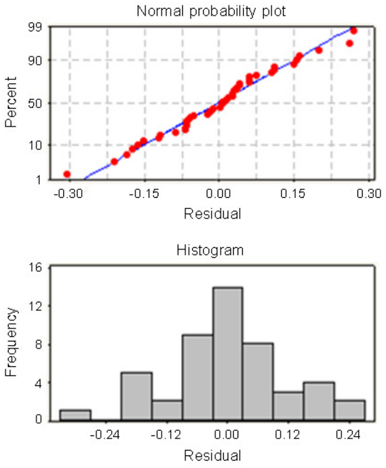

Fig. 4. Residual plots for R_a.

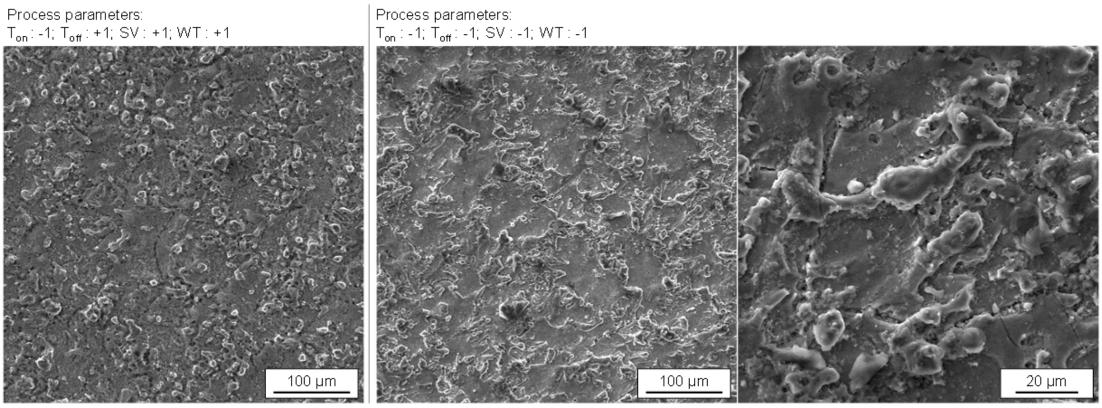

Fig. 5. SEM images showing surface morphology for different cutting conditions.

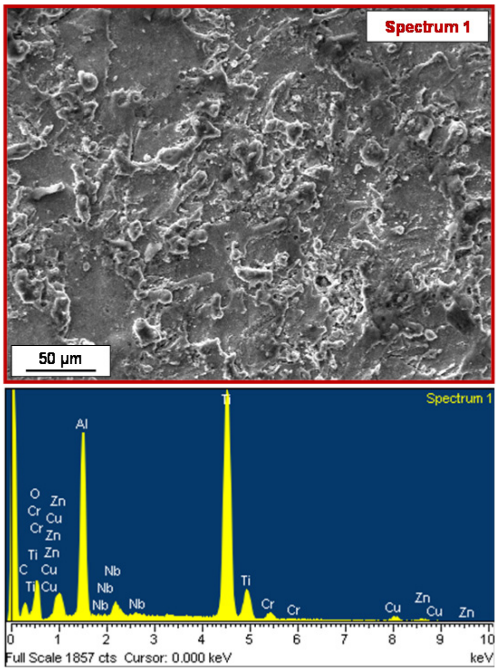

Fig. 6. EDS semi-quantitative elemental analysis on a WEDMed surface.

Although the variations of roughness indices are relatively small, some significant effects of process parameters on surface morphology were detected, as expected from the roughness measurements. Figure 5 shows an example of WEDMed surfaces. From the images, it was observed that the process produces pockmarks and some craters on the surface. The deterioration of the surface is probably due to the high pulse current (with consequent amount of heat energy) transferred to the sample surface, with more melted material. EDS analysis (in Figure 6) detected the basic elements constituting the γ-TiAl alloy, plus some residues of the wire material.

When investigating the surface quality/integrity of machined components, crust/recast layer analyses were also performed. For all those tests, no statistically significant variations in terms of hardness results were achieved (as shown in Figure 7).

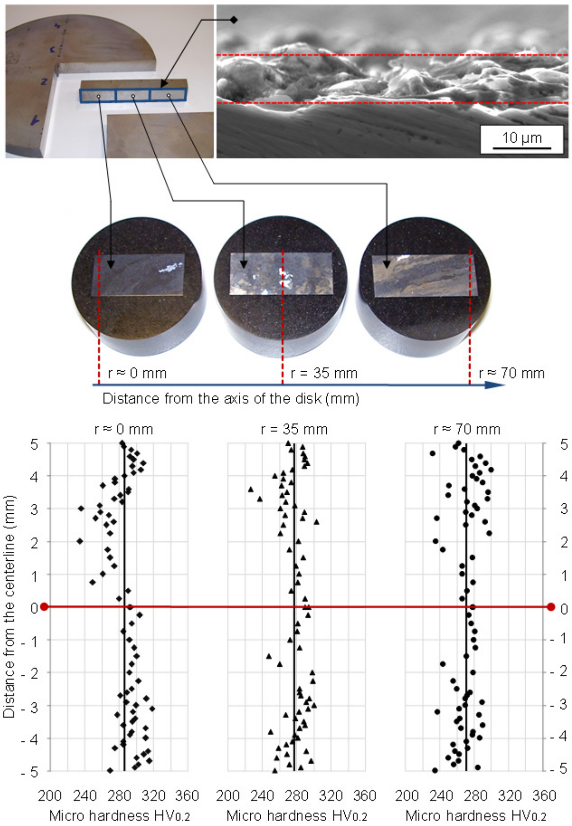

Fig. 7. Typical µ-hardness measurements and recast layer evaluation.

The obtained results were compared with data on WEDM of γ-TiAl available in literature [18-20]. In [18], a trim cutting operation of a lamellar gamma titanium aluminide was studied. The objective was to achieve desired surface finish and dimensional accuracy without sacrificing productivity.

Pulse on time, peak current, dielectric flow rate, and the effective wire offset were considered as process parameters, while the trim cutting speed, surface finish, and dimensional shift were assumed as response parameters. The process was successfully modelled using RSM, and the model adequacy checking was also performed. Finally, an optimization was carried out by means of a Pareto optimization algorithm. It was observed that the surface quality decreases as the cutting speed increases. The authors of [19] analyzed the results of single pass (WEDM) cutting, and they modelled the process using an additive model to predict the response parameters (i.e. cutting speed, surface finish and dimensional deviation) as a function of different control parameters. Pulse on time, pulse off time, peak current, servo-reference voltage, wire tension and dielectric flow rate (discharge pressure) were chosen as inputs. It has been noted that both surface roughness and dimensional deviation are independent of pulse off time. Finally, the process was optimized using constrained optimization and Pareto optimization algorithm. In [20], an optimization strategy based on a feed-forward neural network was used to model the WEDM process. The ANN model was applied to predict the response parameters (cutting speed, surface finish and wire offset) for all possible combinations of input factors (pulse on time, pulse off time, peak current, servo-reference voltage, wire tension and dielectric flow rate). In all the different proposed models, the effect of T_{on} on R_a is undoubtedly recognized. Less common is the analysis of other roughness parameters like R_{sk}.

4. Conclusions

Wire electrical discharge machining tests were carried out on a gamma titanium aluminide ingot. Four process variables were varied during the tests (namely: pulse on time, pulse off time, servo-reference voltage and wire tension). The effect of such parameters on the generated surface finish was investigated by means of ANOVA and regression models. Overall, it is possible to state that all the considered variables affect directly, or indirectly by means of interactions, the surface roughness indices. It is also worth to underline that the combined optimization of R_a, R_t, and R_{sk} appears to be a difficult task, due to the counteracting effects of input parameters. Future studies will be focused on maximizing the productivity while keeping the roughness parameters within the desired limits for specific applications.

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