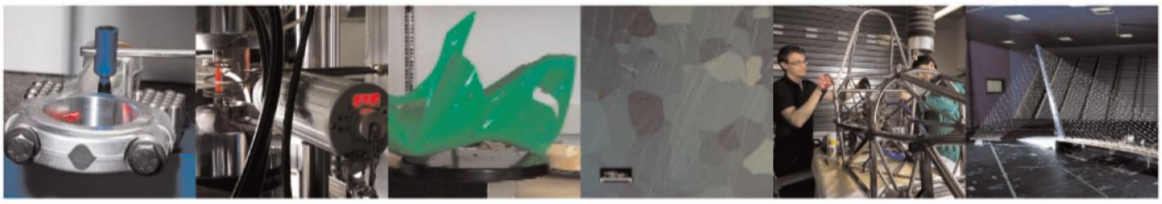


Micro-Abrasive Water Jet and Micro-WEDM Process Chain Assessment for Fabricating Microcomponents

Modica, F.; Basile, V.; Vigano, F.; Arleo, F.; Annoni, M.; Fassi, I.

This is a post-peer-review, pre-copyedit version of an article published in JOURNAL OF MICRO- AND NANO-MANUFACTURING, 7/1, on April 11, 2019. The final authenticated version is available online at: https://doi.org/10.1115/1.4042966

https://asmedigitalcollection.asme.org/micronanomanufacturing/article/doi/10.1115/1.4042966/725630/MicroAbrasive-Water-Jet-and-MicroWEDM-Process

Micro-Abrasive Water Jet and Micro-WEDM Process Chain Assessment for Fabricating Microcomponents

Francesco Modica[1]
STIIMA-CNR,
Institute of Intelligent Industrial Technologies and Systems for Advanced Manufacturing,
National Research Council of Italy,
Via Paolo Lembo 38F,
Bari 70124, Italy
e-mail: francesco.modica@stiima.cnr.it

Vito Basile
STIIMA-CNR,
Institute of Intelligent Industrial Technologies and Systems for Advanced Manufacturing,
National Research Council of Italy,
Via Paolo Lembo 38F,
Bari 70124, Italy
e-mail: vito.basile@stiima.cnr.it

Francesco Viganò
Department of Mechanical Engineering,
Politecnico di Milano,
Via Giuseppe La Masa, 1,
Milano 20156, Italy
e-mail: francesco.vigano@polimi.it

Francesco Arleo
WatAJet S.r.l.,
Via Tomasetto, 31,
Besnate, VA 21010, Italy
e-mail: francesco.arleo@watajet.com

Massimiliano Annoni
Department of Mechanical Engineering,
Politecnico di Milano,
Via Giuseppe La Masa, 1,
Milano 20156, Italy
e-mail: massimiliano.annoni@polimi.it

Irene Fassi
Mem. ASME
STIIMA-CNR,
Institute of Intelligent Industrial Technologies and Systems for Advanced Manufacturing,
National Research Council of Italy,
Via Alfonso Corti 12,
Milano 20133, Italy
e-mail: irene.fassi@stiima.cnr.it

The capability to manufacture high-precision components with microscale features is enhanced by the combination of different micromanufacturing processes in a single process chain. This study explores an effective process chain that combines micro-abrasive water jet (μ-AWJ) and microwire electrical discharge machining (μ-WEDM) technologies. An experimental spring component is chosen as a leading test case, since fine geometric features machining and low roughness on the cut walls are required. The advantages deriving from the two technologies combination are discussed in terms of machining time, surface roughness, and feature accuracy. First, the performances of both processes are assessed by experimentation and discussed. Successively, different process chains are conceived for fabricating two test cases with different sizes, displaying some useful indications that can be drawn from this experience. [DOI: 10.1115/1.4042966]

1 Introduction

The demand of high-precision components with microscale features (HPμSF) [1] and challenging quality specifications (reliability, cost, reproducibility, key geometric features accuracy, and surface roughness) is growing due to the increase of applications in many fields such as optics, automotive, energy, and biomedicine. Examples of microscale features are thin and/or tapered walls, high aspect ratio microchannels, holes, pillars, sharp edges, rounded surfaces, pockets, etc. HPμSF product examples are microfluidics devices, i.e., lab-on-chip, micro-electro-mechanical systems, stents, injector nozzles, micro-impellers, medical needles, microtools and molds, microgears, hearing aids, micrograppers, clockwork frames, etc. [1,2]. The production of such components requires the development of new methods and technologies capable of higher precision, quality assurance, and control on products (metrology). Uhlmann et al. [2] focused on the microproduction process chain and identified several criteria to succeed in manufacturing of HPμSF components. One of these criteria is the hybrid manufacturing development [3] which can be achieved through hybrid machine tool concepts and/or the combination of different manufacturing technologies, achieving higher precision along with machining time and costs reduction.

Two emerging nonconventional technologies for HPμSF manufacturing are the micro-abrasive water jet (μ-AWJ) and the microwire electrical discharge machining (μ-WEDM) [4,5].

Abrasive water jet and μ-AWJ are used to machine a wide variety of materials, brittle and ductile, such as steel, titanium and almost all metal alloys, as well as ceramic, glass, stone, polymers, composites, and multilayers quite easily and reasonably quickly, by using water enriched with abrasive microparticles [6]. Immediately downstream the cutting head, the jet made of high-speed water and abrasive particles (e.g., Garnet) has a usual diameter ranging from 0.70 mm to 1.20 mm in AWJ and reducing down to 0.20 mm in μ-AWJ. In the latter, small orifices and proportionally finer abrasives [2] are adopted to reduce the kerf width down to 0.25 mm. The surface roughness mainly depends on the abrasive size, since Ra = 1 μm can be achieved with abrasive size between 10 and 40 μm [7], and on the process feed rate [8]. The machining areas are reduced and high-precision handling systems are exploited, thus achieving a positioning repeatability below 4 μm [8]. Nevertheless, this technology may be poor in dimensional accuracy and surface quality along the thickness when small features are considered on thick workpieces, since the jet is not a shape-defined tool.

Micro-electrical discharge machining and μ-WEDM are generally adopted in microfeatures machining on hard electroconductive materials. A series of electrical sparks remove material from the workpiece by melting and evaporation. This technology offers the chance to accomplish high accuracy in complex three-dimensional microfeatures although it is highly time-consuming [9].

The aim of this study is to exploit the advantages offered by the combination of both technologies (AWJ and WEDM), thus compensating their single drawbacks. μ-AWJ and μ-WEDM processes have different performance that can be combined to increase the

[1]Corresponding author.

Table 1 Process parameters and cutting quality levels (example) in μ-AWJ according to ISO/TC44N1770

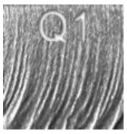
Parameters		Feed rate (mm/min) for cutting quality levels				
Thickness (mm)	Focuser diameter (mm)					
2	0.3			171	123	96
	0.2			51	36	27
4	0.3			78	54	42
	0.2			24	15	12

Table 2 Microwire electrical discharge machining technological parameters

Process regime		Roughing	Semifinishing	Finishing	Fine-Finishing
Sarix energy level	(index)	365	105	100	13
Polarity	(±)	+	+	+	+
Pulse width	(μs)	5	4	2	1
Frequency	(kHz)	120	150	180	160
Current	(index)	60	80	40	80
Voltage	(V)	130	110	82	80
Gap	(index)	75	90	70	72
Gain	(index)	80	9	7	14
Feed rate	(mm/min)	*5.6*	*1.6*	*0.8*	*1.1*
Wire traction	*%*	*30*	*30*	*30*	*30*
Wire speed	*%*	*20* (11.1 mm/s)	*20* (11.1 mm/s)	*20* (11.1 mm/s)	*20* (11.1 mm/s)
Stock allowance	(mm)	0.2 / 0.1 / 0.05	0.2 / 0.05 / 0.02	0.2 / 0.02 / 0.01	0.2 / 0.02 / 0.01

capability of a process chain for HPμSF components manufacturing. In this paper, a combination of μ-AWJ and μ-WEDM technologies is conceived, the process chain is developed, and finally assessed for a significant case study.

2 Experimental Setup

The experimental setup involved two different machines: Daetwyler Microwaterjet F4 and Sarix μ-EDM SX200. The state of the art in μ-AWJ technology has been characterized by using one of the most recent and performing machines, equipped with a double cutting area of 500×600 mm and a handling system positioning precision of ± 2 μm. The aim of the experimental campaign is to point out the performances of μ-AWJ in terms of maximum achievable quality with respect to productivity, which is closely related to the feed rate. Therefore, the machine has been equipped with the two smallest cutting head configurations commercially available, namely the ones with, respectively, a focuser diameter (and therefore an outflowing jet diameter) of $\varnothing$ 0.3 mm and $\varnothing$ 0.2 mm, referred to as CH03 and CH02.

For every cutting head configuration, most of the process parameters have been kept fixed at their optimal level in order to maximize the cutting performances. The only variable parameter is the feed rate since it is the main influencing factor on the cut edge quality (the slower the higher quality) [10] and it is directly related to productivity. This parameter is varied as shown in Table 1, on three different levels in order to obtain progressively improving cutting quality according to ISO/TC 44 N 1770 (Q3 medium quality, Q4 good quality, and Q5 excellent quality).

The constant parameters are: water pressure 350 MPa, stand-off distance 0.35 mm, and abrasive #230 mesh (Barton Garnet).

The abrasive mass flow rates are 71 and 17 g/min at CH03 and CH02, respectively. Preliminary tests have been performed through straight cuts of 25 mm long on an austenitic stainless steel (AISI301), 2 mm thick and 4 mm thick. Three replications for each level have been performed.

A state of the art μ-EDM machine has been used for the experiments (Sarix μEDM SX200). The machine can perform different μ-EDM approaches such as drilling, milling, sinking, and wire. In particular, the machine is equipped with μ-WEDM unit with a brass wire having a diameter of 0.2 mm and adopting hydrocarbon oil as dielectric fluid for the flushing. For this equipment, the μ-WEDM is usually adopted to machine the tool electrode (typically a tubular or solid rod and used in the other approaches) to a desired shape, reducing the rod diameter or giving a more complex shape. Nevertheless, it is also possible to use it for directly machining the workpiece.

Microwire electrical discharge machining has been tested with four different pulse energy regimes (roughing, semifinishing, finishing, and fine-finishing), presenting the technological parameters shown in Table 2, in order to measure the process performance (speed, kerf, and surface roughness). In particular, the roughing regime is used for cutting the workpiece leaving enough stock allowance for the following finishing tasks, while the other regimes are adopted for improving surface roughness. For this reason, the regimes have been tested with different stock allowance (Fig. 1), as reported in Table 2.

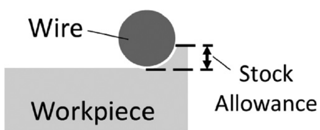


Fig. 1 Stock allowance

Table 3 Test results for μ-AWJ

Machining parameters				Results				
			Quality index	Surface roughness Ra				
Thickness	Focuser diameter	Feed rate	↑Q3→Q5	Average ± SD[a]	Worst	Kerf width	Wall taper angle	Machining time
(mm)	(mm)	(mm/min)	(index)	(μm)		(mm)	(deg)	(min)
2	0.3	171	Q3	1.40 ± 0.13	1.53	0.314	0.54	0.15
		123	Q4	1.37 ± 0.21	1.60	0.283	0.61	0.20
		96	Q5	1.51 ± 0.18	1.70	0.275	0.73	0.26
	0.2	51	Q3	1.31 ± 0.24	1.55	0.236	0.21	0.49
		36	Q4	1.22 ± 0.13	1.36	0.246	0.14	0.69
		27	Q5	1.32 ± 0.23	1.57	0.240	0.11	0.93
4	0.3	78	Q3	1.31 ± 0.23	1.56	0.289	0.38	0.32
		54	Q4	1.24 ± 0.23	1.51	0.305	0.18	0.46
		42	Q5	1.56 ± 0.30	1.88	0.319	0.10	0.60
	0.2	24	Q3	1.31 ± 0.33	1.66	0.253	0.07	1.04
		15	Q4	1.22 ± 0.24	1.46	0.263	−0.02	1.67
		12	Q5	1.13 ± 0.19	1.31	0.276	−0.09	2.08

[a]Average and standard deviation along the thickness.

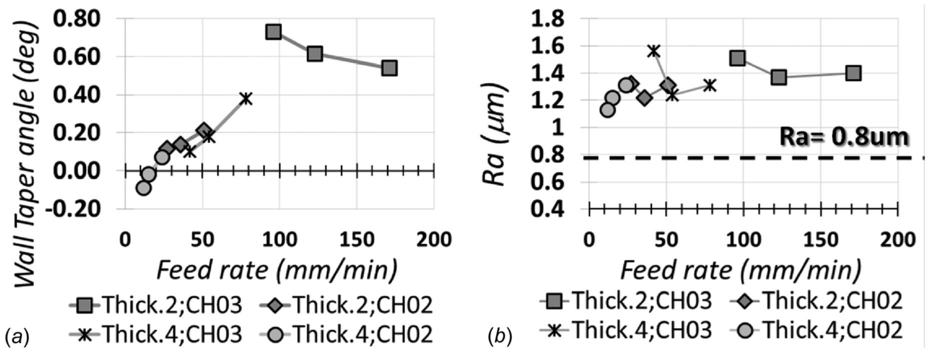


Fig. 2 Micro-abrasive water jet performance for plate thickness of 2 mm: (*a*) wall taper angle versus feed rate and (*b*) Ra versus feed rate

3 Micro-Abrasive Water Jet

The tests results are reported in Table 3. At different process parameters and thickness values, several measurements have been performed of surface roughness Ra, kerf width, wall taper angle, and machining time.

The Ra roughness has been measured by Mahr Perthometer PGK instrument (Göttingen, Germany) (with a conical stylus of 90 deg and a tip radius of 2 μm) at different distances from the top surface (jet side): 0.1, 0.2, 1.0, 1.8, and 1.9 mm (thickness 2 mm); 0.1, 0.2, 2.0, 3.8, and 3.9 mm (thickness 4 mm).

Table 4 Test results for μ-WEDM

				Plate thickness 2 mm			Plate thickness 4 mm		
	Stock allowance	Kerf	Standard deviation	Process speed	Ra	Standard deviation	Process speed	Ra	Standard deviation
Units	(mm)	(mm)	(mm)	(mm/min)	(μm)	(μm)	(mm/min)	(μm)	(μm)
Roughing	0.2	0.224	0.002	0.60	2.5	0.16	0.44	2.1	0.10
	0.1			1.61	2.4	0.03	0.94	2.2	0.04
	0.05			2.48	2.9	0.16	1.71	2.4	0.03
Semifinishing	0.2	0.213	0.001	0.11	—	—	—	—	—
	0.05			0.26	0.8	0.03	0.14	0.7	0.01
	0.02			0.35	0.7	0.03	0.26	0.6	0.02
Finishing	0.2	0.212	0.001	0.02	—	—	—	—	—
	0.02			0.23	0.5	0.01	0.12	0.5	0.01
	0.01			0.29	0.5	0.00	0.18	0.5	0.03
Fine-finishing	0.2	0.213	0.001	0.01	—	—	—	—	—
	0.02			0.13	0.5	0.01	0.04	0.4	0.01
	0.01			0.14	0.5	0.02	0.05	0.5	0.00

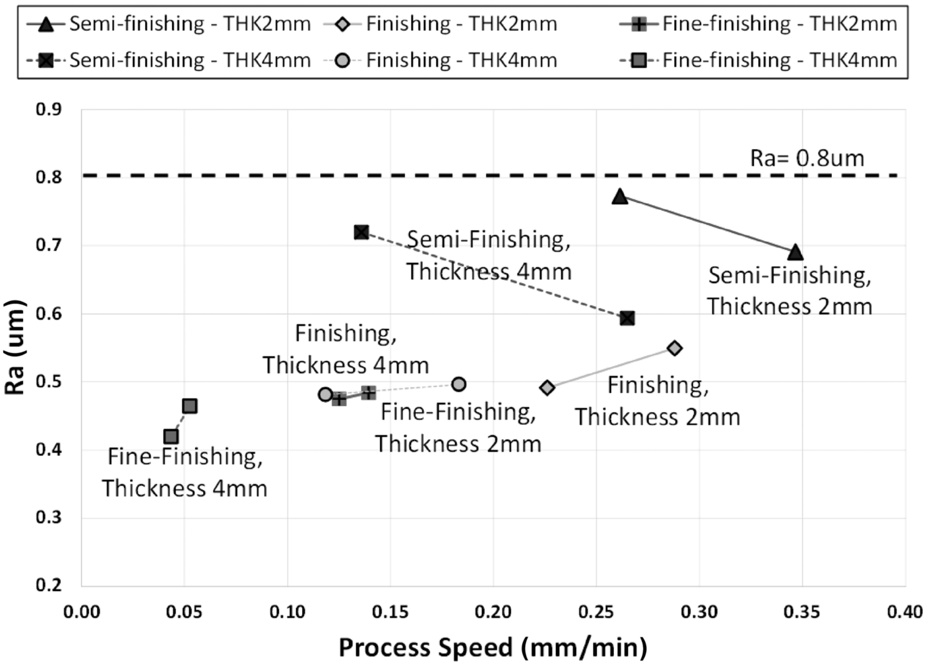


Fig. 3 Microwire electrical discharge machining finishing technologies: average process speed versus surface roughness for two levels of stock allowance

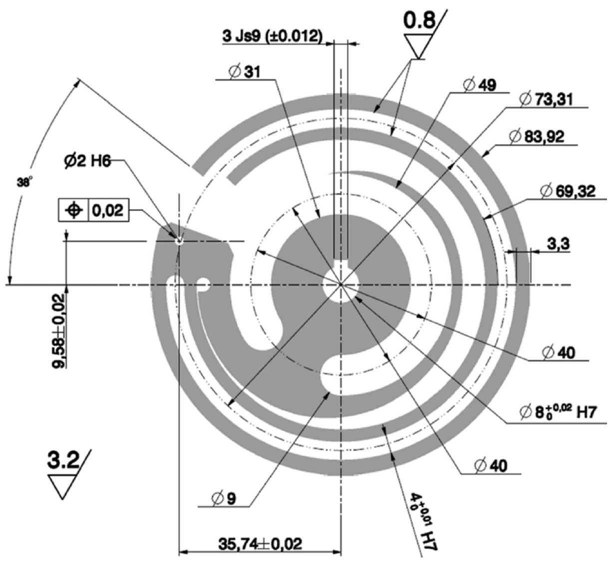


Fig. 4 Drawing of the spring

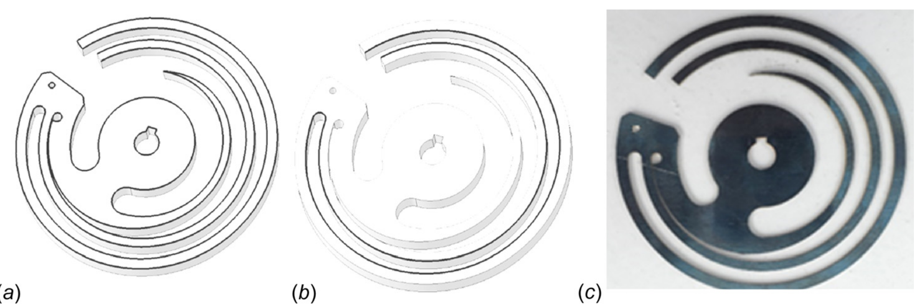
Table 3 shows the Ra average and standard deviation along the kerf thickness. The maximum Ra value (Table 3) is always found at the kerf bottom, as a result of the jet progressive energy and coherence loss [8]. Higher feed rate results in lower kerf widths, higher wall taper angles (Fig. 2(*a*)), and higher Ra (Fig. 2(*b*)) with a clear exception for thickness 2 mm and CH03, where trends are opposite.

4 Microwire Electrical Discharge Machining

Table 4 reports the summary of the tests results in term of kerf dimension, process average speed, and surface roughness (Ra). It must be underlined that the average process speed differs from the feed rate because during the erosion the machine control system regulates the speed in order to recover from short circuits that occasionally occur.

The graph of Fig. 3 for finishing regimes reports the Ra in relation to the average process speed when the stock allowance is changed.

As expected, for any regime the process average speed decreases when stock allowance or plate thickness rises, due to the augmented surface involved into the erosion process. On the contrary, the surface roughness is improved when the plate thickness or the stock allowance increase.



(*a*) (*b*) (*c*)

Fig. 5 Toolpaths: (*a*) rough trimming by μ-AWJ, (*b*) finishing by μ-WEDM, and (*c*) μ-AWJ machined sample

Table 5 Process chain performances for a 2-mm-thick plate

Combination #		1	2	3	4	5
Process chain (workpiece thickness 2 mm)		AWJ CH03	AWJ CH02	AWJ CH03 + WEDM semifinish	AWJ CH02 + WEDM finish	AWJ CH03 + WEDM finish
Tool path total length	(mm)	1252.8	1252.8	1252.8	1252.8	1252.8
Tool path finishing length (Ra target = 0.8 μm)	(mm)	0.0	0.0	415.3	415.3	415.3
Machining time in rough trimming	(min)	7	35	7	35	7
Machining time in finishing	(min)	0	0	1199	1837	1837
Total machining time	(min)	7	35	1206	1872	1844
Ra rough trimming	(μm)	1.53	1.36	1.53	1.36	1.53
Ra finishing	(μm)	1.53	1.36	0.77	0.49	0.49
Wall taper angle, rough trimming	(deg)	0.54	0.14	0.54	0.14	0.54
Wall tapering finishing	(deg)	0.54	0.14	0	0	0

Table 6 Process chain performances for the scaled component with a thickness of 4 mm

Combination #		1	2	3	4	5
Process chain (workpiece thickness 4 mm)		AWJ CH03	AWJ CH02	AWJ CH03 + WEDM semifinish	AWJ CH02 + WEDM finish	AWJ CH03 + WEDM finish
Tool path total length	(mm)	313.2	313.2	313.2	313.2	313.2
Tool path finishing length (Ra target = 0.8 μm)	(mm)	0.0	0.0	103.8	103.8	103.8
Machining time in rough trimming	(min)	4	26	4	26	4
Machining time in finishing	(min)	0	0	392	876	876
Total machining time	(min)	4	26	396	902	880
Ra rough trimming	(μm)	1.56	1.31	1.56	1.31	1.56
Ra finishing	(μm)	1.56	1.31	0.72	0.48	0.48
Wall taper angle rough trimming	(deg)	0.76	−0.17	0.76	−0.17	0.76
Wall tapering finishing	(deg)	0.76	−0.17	0	0	0

The surface quality is mainly influenced by two factors: crater size/shape and amplitude of the wire vibration. The first factor merely depends on the pulse energy, whereas the second factor is a dynamic complex combination of wire traction, process speed, guidance of the wire, workpiece position, pulse energy and its spatial distribution, flushing. In particular, the workpiece tends to reduce the wire vibration giving a sort of guidance to the wire, especially when plate thickness and stock allowance increase. However, the wire vibration seems to be dominant when the pulse energy and the stock allowance decrease limiting the minimum Ra achievable. It is worth noticing that the lowest pulse energies are usually adopted in a grinding configuration where the wire is guided during the process. Unfortunately, due to the presence of the guide, the grinding configuration is not suitable for machining internal features.

5 Case Study and Processes Combinations

The HPμSF component assumed as case study for the assessment of μ-AWJ/μ-EDM combination is a spring, which is part of an innovative actuation mechanism (Fig. 4). Two values of thickness have been assumed for tests: 2 and 4 mm with a nominal tolerance of ±0.035 mm.

The spring has an external diameter of ∅ 83.92 mm and a cam slot with an angular range of 300 deg, on a diameter of ∅ 73.32 mm and a width of 4 mm, with tolerance H7. This latter feature requires high-precision and high surface finishing of the slot walls. The required surface roughness Ra of the slot walls is 0.8 μm or lower. A second version of this component presents the same geometry scaled of a factor of four but with the same thickness. Both versions have been used for evaluating the combinations of the processes.

Starting from the steel sheet, the manufacturing strategy conceived for this component considers a first μ-AWJ rough trimming (through thickness cut, Fig. 5(*a*)) with a nominal oversize of 0.02 mm and a finishing performed on the high-precision cam slot by μ-WEDM (Fig. 5(*b*)). This strategy allows exploiting the high machining speed of μ-AWJ and the high accuracy and surface finishing (at lower speed) of μ-WEDM. In order to preserve the workpiece alignment precision from μ-AWJ to μ-WEDM, a customized fixture has been designed to hold and reference the spring workpiece during the μ-WEDM finishing setup. Using the process performance assessed in Sec. 3 for μ-AWJ and Sec. 4 for μ-WEDM, three different combinations of processes have been conceived for fabricating the first test case with a thickness of 2 mm (Table 5) and the scaled test case with a thickness of 4 mm (Table 6). The first two columns of the tables are related to the use of the μ-AWJ with the configuration CH03 and CH02, respectively. Although μ-AWJ is very fast with both configurations, it is possible to notice that by using only the μ-AWJ the target of Ra = 0.8 μm and zero wall tapering is not respected. The last three columns show the performance of the following combination: μ-AWJ CH03 for rough trimming followed by μ-WEDM semifinishing, μ-AWJ CH02 for rough trimming followed by μ-WEDM finishing, μ-AWJ CH03 for rough trimming followed by μ-WEDM finishing.

For both test cases, all the last three configurations respect the requirements for Ra and wall tapering. However, the total machining time is dramatically longer for the first test case, while it remains acceptable for the scaled one. Because of the dimensions of the first test case, it is reasonable to look for alternatives to the μ-WEDM process. Due to the small dimension with high aspect ratio of some features of the scaled test case, the presented combinations result effective for its fabrication.

6 Conclusions

This study has shown the advantages of the combinations of two nonconventional technologies: μ-AWJ and μ-EDM. In particular, the experimentation of μ-AWJ has shown that the process is very fast and can obtain valuable surface quality (Ra around 1 μm) and low wall tapering. However, the Ra gets slightly worse along the plate thickness. On the contrary, the μ-WEDM test has displayed that the process can reach finer surface roughness (Ra less than 0.5 μm) without wall tapering but with a considerable machining time (hundred times more than μ-AWJ). For both the test cases, the combination of the two processes fulfills the required surface quality and geometrical accuracy. However, the conceived process chains need a significant time for machining that only for the scaled test case can be considered effective.

Nomenclature

AWJ–μ-AWJ = abrasive water jet and micro-abrasive water jet
EDM–μ-EDM = electrical discharge machining and micro-electrical discharge machining
HPμSF = high-precision components with microscale features
Ra = surface roughness
WEDM–μ-WEDM = wire electrical discharge machining and microwire electrical discharge machining

References

[1] Hansen, H. N., Carneiro, K., Haitjema, H., and De Chiffre, L., 2006, "Dimensional Micro and Nano Metrology," CIRP Ann., **55**(2), pp. 721–743.

[2] Uhlmann, E., Mullany, B., Biermann, D., Rajurkar, K. P., Hausotte, T., and Brinksmeier, E., 2016, "Process Chains for High-Precision Components With Micro-Scale Features," CIRP Ann. Manuf. Tech., **65**(2), pp. 549–572.

[3] Lauwers, B., Klocke, F., Klink, A., Tekkaya, E., Neugebauer, R., and Mcintosh, D., 2014, "Hybrid Processes in Manufacturing," CIRP Ann., **63**(2), pp. 561–583.

[4] Skoczypiec, S., 2017, "The Role of Unconventional Manufacturing Processes in Modern Manufacturing Chain," *Innovations in Management and Production Engineering*, R. Knosala, ed., Publishing House of the Polish Society for Production Management, Opole, Poland, pp. 815–826.

[5] Puri, A. B., 2017, "Advancements in Micro Wire-Cut Electrical Discharge Machining," *Non-Traditional Micromachining Processes*, Chap. 4, Springer, Cham, Switzerland.

[6] Matsumura, T., Muramatsu, T., and Fueki, S., 2011, "Abrasive Water Jet Machining of Glass With Stagnation Effect," CIRP Ann. Manuf. Tech., **60**(1), pp. 355–358.

[7] Jafar, R. H. M., Nouraei, H., Emamifar, M., Papini, M., and Spelt, J. K., 2015, "Erosion Modeling in Abrasive Slurry Jet Micro-Machining of Brittle Materials," J. Manuf. Processes, **17**, pp. 127–140.

[8] Annoni, M., Arleo, F., and Viganò, F., 2017, "Micro-Waterjet Technology," *Micro-Manufacturing Technologies and Their Applications*, I. Fassi and D. Shipley, eds., Springer, Cham, Switzerland, Chap. 5.

[9] Modica, F., Marrocco, V., and Fassi, I., 2017, "Micro-Electro-Discharge Machining (Micro-EDM)," *Micro-Manufacturing Technologies and Their Applications*, I. Fassi and D. Shipley, eds., Springer, Cham, Switzerland, Chap. 6.

[10] Momber, A. W., and Kovacevic, R., 1998, *Principles of Abrasive Water Jet Machining*, Springer, London.