Chapter

Analysis of Surface Roughness of EN AW 2024 and EN AW 2030 Alloys after Micromachining

Francisco Mata and Issam Hanafi

Abstract

Micromachining is the most suitable technology for the production of very small components (micro-components) in the industry. It is a high-precision manufacturing process with applications in various industrial sectors, including machine building. This chapter presents the experimental study of the roughness (Ra and Rt) of aluminum alloys using a specific micro-turning process. The roughness measurements carried out show how it is possible to achieve very good surface qualities up to 0.05 mm diameter. For lower diameters, the surface quality worsens and the shape defects increase (conicity) due to the very low rigidity of the workpiece, which makes it very sensitive when passing through the forming process. The fundamental objective of this research is to analyze the surface quality of the finishes obtained in these micromachining processes and to evaluate their suitability to the specifications required by the mechanical industry (roughness, presence of burrs, shape and geometry, etc.). Predictive roughness models are proposed, with a good degree of approximation, to help characterize micromachining processes.

Keywords: micromachines, micro-turning, miniaturization, models

1. Introduction

The traditional machine concept, consisting of large mechanical elements with high energy consumption, low precision, and little degree of automation, has given way to much more complex realities in the integration of technologies (mechanical, pneumatic, electronic, etc.), in the reduction of sizes and consumption, and of course, in the possibility of performing high-precision operations with exhaustive controls. In this context, it is possible to speak of micromachines, which are small machines to develop operations of precision and are integrated by mechanisms and components of very small size. Consider, for example, the machinery of a watch or the injection systems used in the automotive industry. It is therefore necessary to manufacture components of very small dimensions, that is, micro-components for applications in the mechanical, biomedical, automotive, or mechatronic industries, among others.

The development of new materials with high performance, their study at micro- and nanotechnological scale, and the continuous attempt to achieve as compact designs as possible support the need to advance manufacturing processes on this scale [1]. The miniaturization of components has become a specialty within the design and micro-manufacturing, a discipline also differentiated, involving machines, tools, and measuring equipment that must necessarily be adapted to the particularities of this type of conformation. This implies a growing demand for the integration needs of microscale components manufactured using different materials, including metals and their alloys [2–5].

Micro-fabrication can be carried out using adapted traditional shaping techniques (microinjection), by chip removal in machine tools (using tools of appropriate geometry), or using other advanced conformation techniques (laser, ultrasound, photochemical forming, thermal diffusion, electric discharge, etc.) [5]. Machining meso (<10 mm) and micro (<1 mm) are the most suitable technologies for the production of very small components in the industry [1–7], especially when high surface finishing and dimensional tolerances are required. These are high-precision manufacturing processes with applications in leading sectors such as the following [7, 8]:

- Medical industry: Production of small components that can be used as parts of bone and dental prostheses (implants and micro-implants) or as essential devices for performing surgical operations.

- Electronics industry: Instrumentation and control equipment (sensors, actuators, etc.), telephony components, etc.

- Aerospace industry: Flow control elements, control devices, etc.

- Automotive industry: Small actuators, fuel injection nozzles and injectors, micro-valves and other small components (screws, pins, bearing needles, micro-axes, micro-wheels, etc.), and microsensors for pressure signal collection, temperature, proximity, angular speed, or acceleration. Indeed, the evolution of automobiles in recent decades toward the integration of mechanical and electronic technologies (mechatronics) demands components of very small dimensions for stability control systems, electronic injection, air bag, etc.

- Watchmaking: Micro-mechanisms (wheels, etc.).

- Micromachines: Integrated by microsensors, micro-motors, micro-gears, micro-actuators, etc.

In elements and microelements that have to integrate mechanisms, where there must be contact and relative movement between them, the surface finish becomes critical in addition to the precise dimensional adjustments. The small size of some of these elements and their peculiar shape, together with the specification of a good surface finish that prevents premature wear, requires opting for micro-conforming processes such as turning or milling, essentially. It should be added that the machining of micro-workpieces does not necessarily involve the use of small-volume machine tools ("micro-lathes" or "micro-milling machines"); micromachining operations can be developed in the conventional CNC machines and therefore it is important to carry out experimental studies leading to the characterization of these processes (establishment of limits to ensure the integrity and quality of machined workpieces, definition of appropriate functional cutting parameters, study of the geometry of cutting tools, determination of achievable surface quality levels, etc.)

The study of surfaces is a technique for characterizing materials, which is very useful in practice. Surface roughness is a parameter that has a great influence on the behavior and functionality of mechanical components and on production costs [9, 10], constituting an important quality control variable. Roughness is critical in mechanical contacts in addition to other fields such as fluid circulation or biomedical applications. The surface roughness obtained during the machining process is affected by the cutting parameters, tool wear, and material hardness. To achieve the desired roughness, it is necessary to know the mechanisms of the cutting and detachment of the material and the kinetics of machining processes, which affect the performance of the cutting tools [11].

In most applications of the machined micro-workpieces, high quality is required on shaped surfaces, including dimensional accuracy and surface integrity. For this reason, it is necessary to carry out various investigations with the aim of optimizing the cutting parameters in order to obtain a certain roughness [9, 12] and tolerable formal characteristics (cylindricity).

Conventional micromachining is a flexible approach that can use any material that can be machined [13]. However, it has some restrictions on the development of components [14]. It is therefore necessary to investigate, to develop models that allow to optimize the processes, and to improve the quality of the products and to lower the production costs.

In order to reduce the number of tests required for a complete characterization of micromachining processes, statistical nonlinear regression techniques, numerical strategies based on neural networks or other similar techniques can be used [15–19], which will allow us to establish prediction models and help us to better understand cutting mechanisms. Based on these models, the experimental program can be completed in order to know the particularities of the micromachining processes and to define the corresponding physical cutting models.

In recent times, due to environmental requirements, these processes are carried out in the absence of cutting fluids [20]. However, the total suppression of fluids results in very aggressive process conditions [21–23]. Each alloy has its own characteristics of machinability, which will mark the operational limits of the process. Although conventional machining processes for metals and their alloys are therefore well known, it is not possible to make a direct extrapolation and anticipate what the behavior will be in the event of chip removal operations on very small workpieces. In these cases, the geometry of the tool and the stability of the workpiece (lean:stiff ratio) can significantly influence the results and differentiate the behavior pattern from the conventional machining of standard size workpieces.

The main objective of this research is to analyze the surface quality of the finishes obtained in these micromachining processes and to evaluate their suitability to the specifications required in micro-components of different devices and machines (roughness, presence of burrs, shape and geometry, etc.). Nonlinear models are proposed in this study that can help in the characterization of micromachining processes, depending on the diameter required for a given application as well as the necessary surface quality.

2. Materials

Aluminum (Al) has a combination of properties that make it very useful in mechanical engineering, such as its low density (2700 kg/m3) and its high resistance to corrosion. Its mechanical strength (up to 690 Mpa) can be significantly increased by suitable alloys. Aluminum alloys are a viable alternative in improving flexibility and competitiveness. The current trend is its gradual incorporation into the definition of industrial cycles incorporating high-speed machines, advanced CNC, and specific aluminum alloys. The intrinsic characteristics of aluminum alloys favor high-speed machining with feed and cut speeds much higher than those achieved with ferrous alloys.

	Cu	Mn	Zn	Mg	Fe	Cr	Si	Ti
EN AW 2024	4.15	0.65	0.5	0.69	0.7	0.1	0.45	0.2
EN AW 2030	4.5	1	0.5	1.3	0.7	0.1	0.8	0.2

Table 1.
Chemical composition of tested aluminum alloys.

	EN AW 2024	EN AW 2030
Designation (ISO)	AlCu4Mg1	AlCu4PbMg
Density	2.77	2.82
Modulus of elasticity in N/mm^2	72.4×10^3	73.6×10^3
Mean coefficient of expansion in m/m.°C	22.9×10^{-6}	23×10^{-6}
Thermal conductivity in $W.m/m^2.°C$	120	190

Table 2.
Mechanical properties of tested aluminum alloys.

As far as possible, metal carbide tools should be used for turning, as they offer higher productivity and a longer service life.

This type of alloy has applications in dental prostheses, micro-valves, actuators and other instrumentation components, injectors of different motors, precision mechanisms, and in general, components of micromachines.

Commercial EN AW 2024 and EN AW 2030 aluminum alloys are used for the experiments. Chemical composition and some mechanical properties of tested aluminum alloys are given in **Tables 1** and **2**.

3. Experimental procedure

The micro-turning process has been carried out on an Eclipse CNC Lathe, with a power of 1.5 Kw and 4000 rpm maximum rotation speed of the head (**Figure 1**).

To measure roughness (mean roughness: Ra, and maximum roughness: Rt), given the very small diameter of the machined workpieces, a Talysurf CLI roughness meter (**Figure 2**) has been used for topographic exploration, using an inductive contact sensor or noncontact laser meter. A conventional optical microscope (**Figure 2**) has been used for the observation of conicity and cylindricity.

Figure 1.
Eclipse lathe used in micro-turning tests. Left: Equipment. Right: Example of turning program followed.

For cutting tools, SDCR2020K-07 and finishing insert have been used, with the characteristics reflected in **Figure 3**.

The cutting parameters used were as follows: cutting speed: 500 rpm, feed rate: 0.002 mm/rev, and depth of cut: 0.001 mm. The diameter of the test pieces ranged from 0.5 to 0.025 mm, with lengths ranging from 10 to 5 mm, in order to keep a minimum value of the L/D ratio (length/diameter). **Figure 4** shows some details of turning tests and shows the relative size of machined workpieces.

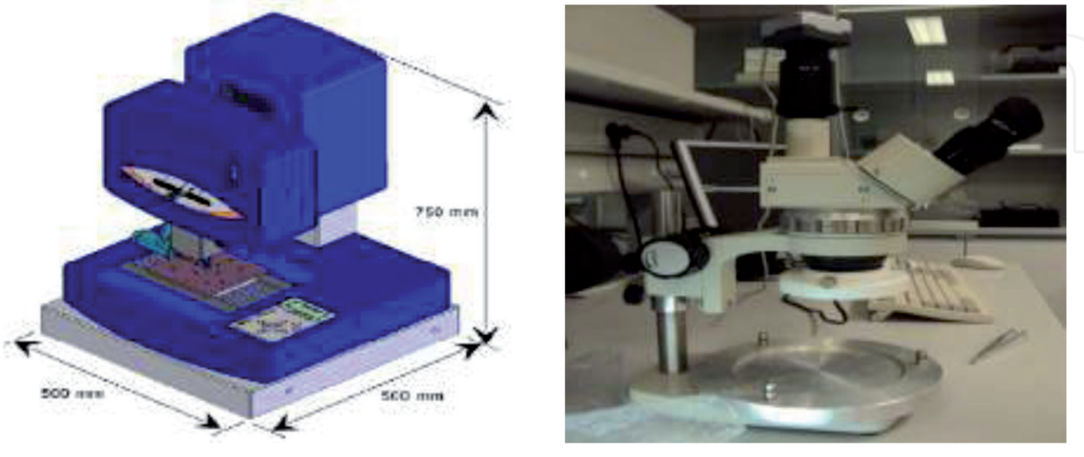


Figure 2.
Measuring equipment. Left: Talysurf CLI roughness meter. Right: Optical microscope.

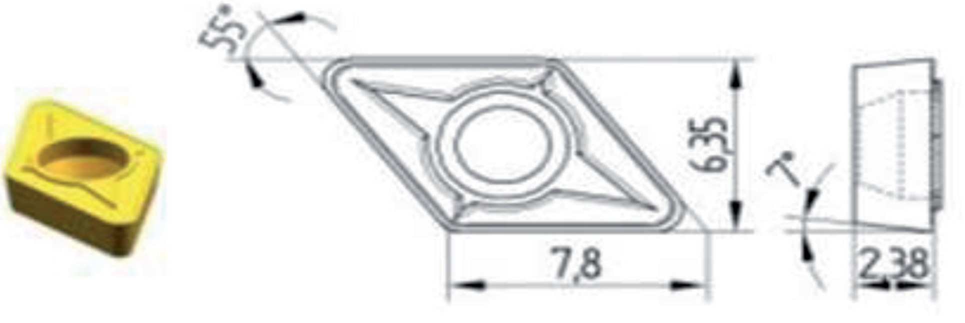


Figure 3.
Cutting tool geometry.

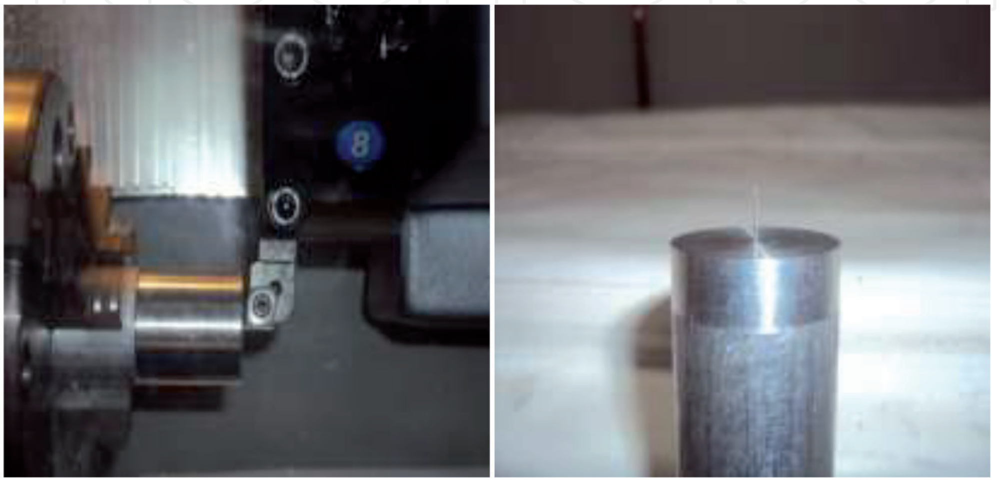


Figure 4.
Details of the experiment. Display of the machined test pieces (0.2 mm in diameter, as shown in the image).

In certain applications, such as those where precise adjustments have to be made in the component assembly process, it is essential to be able to obtain accurate diameters in accordance with the technical specifications laid down in the relevant project. For this purpose, it is necessary to use techniques to characterize the quality of the parts, including the study of roughness, the determination of the degree, or percentage of conicity-cylindricity and dimensional precision.

4. Mathematical models for prediction

Finally, as regards the treatment of the results, it is possible to establish mathematical models of prediction, which can be very useful to characterize the processes, while serving as a practical guide for the development of the same, setting certain cutting conditions, materials, tools, etc. When measuring the accuracy of the estimate and the predictability, account shall be taken of the following:

The sum of squares of errors (SSE), which is the sum of squares of the deviations of the residue values from their sample mean.

Multiple coefficient determination, R^2, and R^2 adjusted, are some common measures in regression analysis, denoting the percentage of variance justified by independent variables. The adjusted R^2 takes into account the size of the data set, and its value is slightly lower than its corresponding R^2.

The validation process was performed by comparing the observed values and the estimated values using the different methods through the mean quadratic error (RMSE).

5. Results and discussion

5.1 Analysis of experimental data

After the micro-turning tests were carried out, the roughness was measured and the cylindrical properties of the machined parts were studied. **Table 3** shows the experimental results of the roughness parameters, Ra and Rt, for the two materials, depending on the diameter of the workpiece.

As can be seen, and especially significantly in the mean roughness (Ra), the roughness is maintained at low and almost constant values as we reduce the diameter of the workpiece, up to 0.2 mm. For lower values, there is an increase in roughness, especially for values of 0.05 mm and below. This increase is due to the low rigidity of the workpieces and the sensitivity to vibrations.

Figure 5 shows an example of roughness profile obtained.

Diameter (mm)	EN AW 2024		EN AW 2030	
	Ra (μm)	Rt (μm)	Ra (μm)	Rt (μm)
0.4	1.4514	26.145	1.4031	21.327
0.2	1.3011	22.308	1.3170	20.196
0.1	1.3821	25.236	1.3392	23.376
0.05	1.4928	22.032	1.4581	22.814
0.025	5.5316	46.173	3.958	38.471

Table 3.
Experimental roughness values.

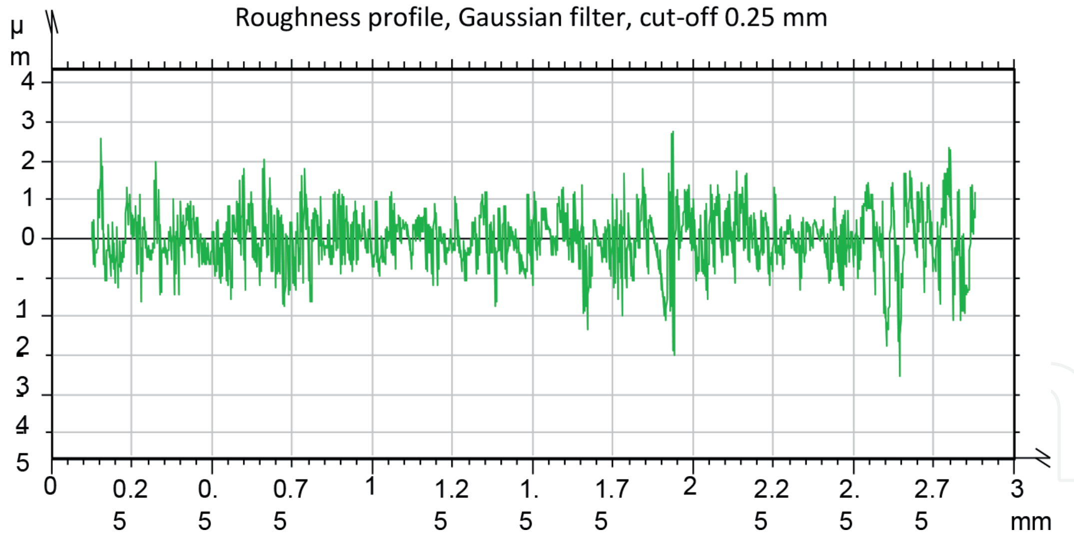


Figure 5.
Example of the obtained roughness profile.

The appearance of the surface and the machining marks can be seen in **Figure 6**.

As regards the preservation of the formal characteristics of the workpieces, the conicity (%) has been calculated with the help of increased images. The conicity, as a function of length and diameter, is calculated using Eq. (1). The results are presented in **Table 4**.

$$c[\%] = 100\frac{D}{L} \tag{1}$$

It is observed that the conicity values are generally low, although they may not become manageable in certain applications. The conicity or "cylindricity defect" is increased by reducing the diameter of the workpiece, mainly due to the increased sensitivity of the workpiece as it passes through the machining process. It can also be seen how the conicity values are always lower in the case of titanium alloy, which may be due to its greater rigidity and its greater ease for micromachining (an interaction of the cutting tool with the micro-workpiece is expected to be somewhat more "fluid," which should probably translate into lower values of the cutting forces).

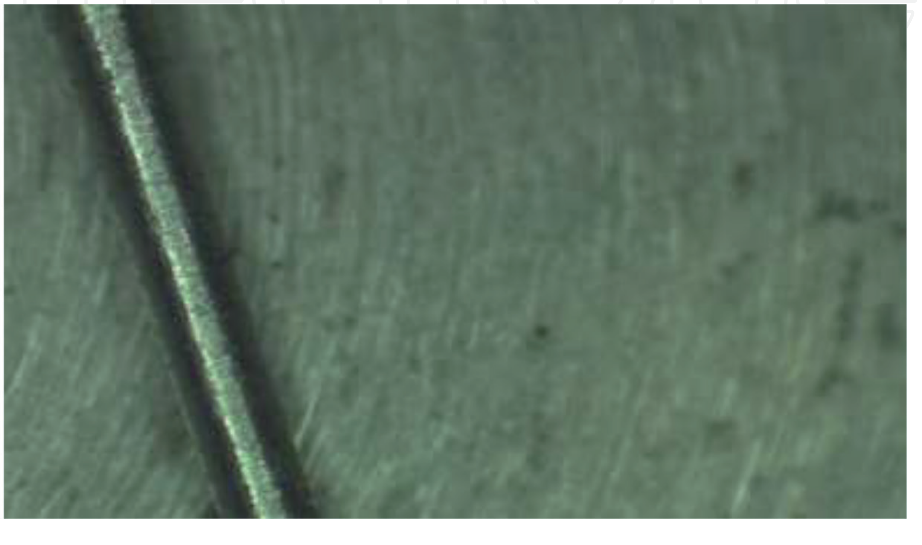


Figure 6.
Workpiece (450 magnifications), diameter: 0.2 mm.

Diameter (mm)	EN AW 2024	EN AW 2030
	Conicity (%)	Conicity (%)
0.4	6.25	5.85
0.2	6.66	6.21
0.1	6.94	6.32
0.05	7.26	6.83
0.025	8.42	7.91

Table 4.
Evolution of conicity according to the diameter of the workpiece.

Figure 7 shows the detail of the graphical treatment performed to measure conicity. It is important to use an appropriate "length-to-diameter" ratio to reduce conicity, vibration and improve the surface quality of machined workpieces.

5.2 Prediction models

The mathematical models developed for the prediction of the roughness parameters, Ra and Rt, are presented below.

$$Ra = 2{,}188 \times 10^{-8} \times d^{-5.167} + 1{,}377 \quad (2)$$

$$Rt = 63{,}98 \times 10^{10} \times \exp(-868{,}9 \times d) + 22{,}4 \times \exp(0{,}3462 \times d) \quad (3)$$

$$Ra = 1{,}35 + \exp(4{,}16 + (-128{,}47) \times d) \quad (4)$$

$$Rt = 21{,}62 + \exp(5{,}45 + (-105{,}037) \times d) \quad (5)$$

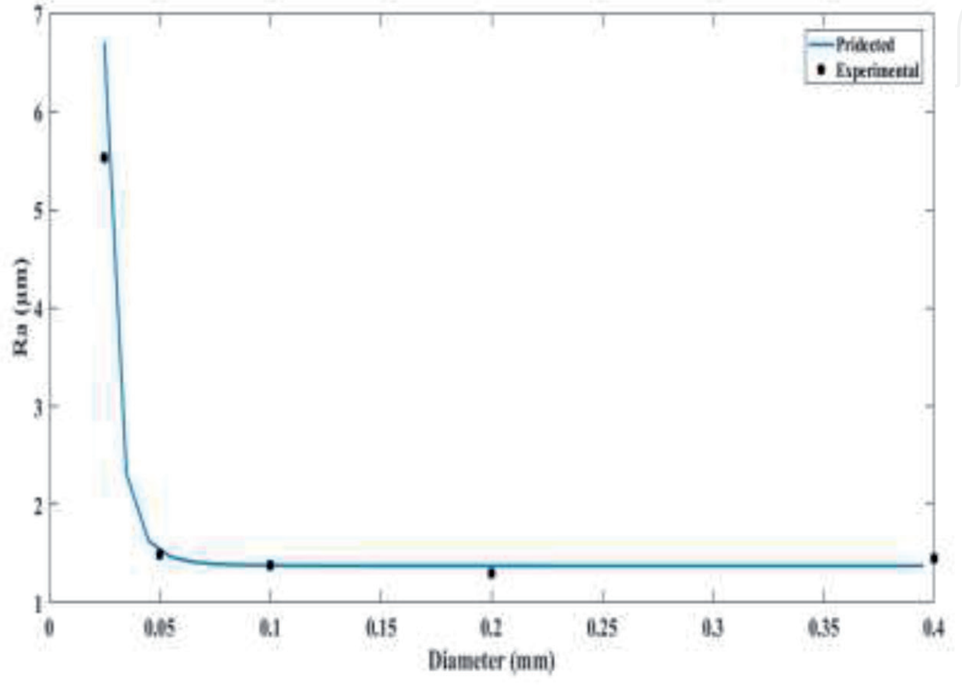
Table 5 reflects the measures of the goodness of the estimate and the predictability, using the parameters SSE, RMSE, R^2, and R^2 adjusted.

As can be seen, the values indicate that the estimates made are generally very good. **Figures 8** and **9** show the experimental roughness values of micromachined

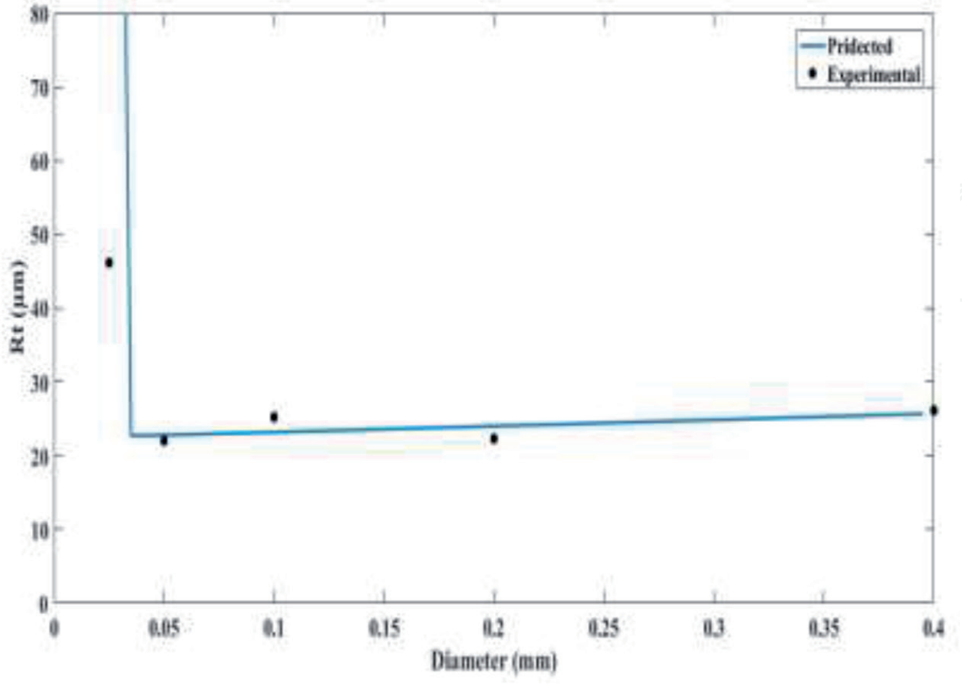
Figure 7.
Obtaining conicity.

Models	SSE	R^2	R^2 adjusted	RMSE
(2)	0.011	0.99	0.99	0.075
(3)	7.824	0.98	0.92	2.797
(4)	0.0040	0.99	0.99	0.0283
(5)	5.1754	0.98	0.98	1.0174

Table 5.
Validation of proposed nonlinear models.

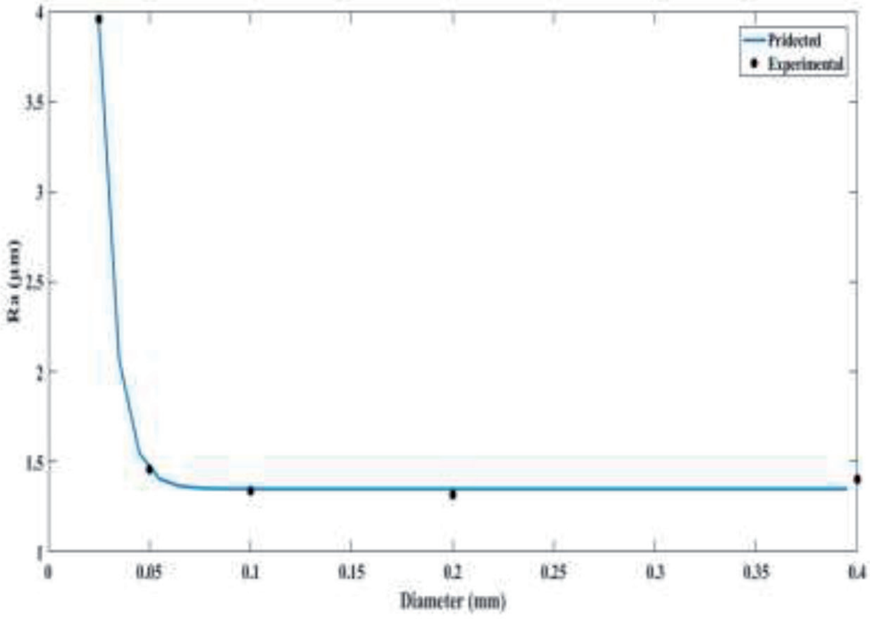


a)

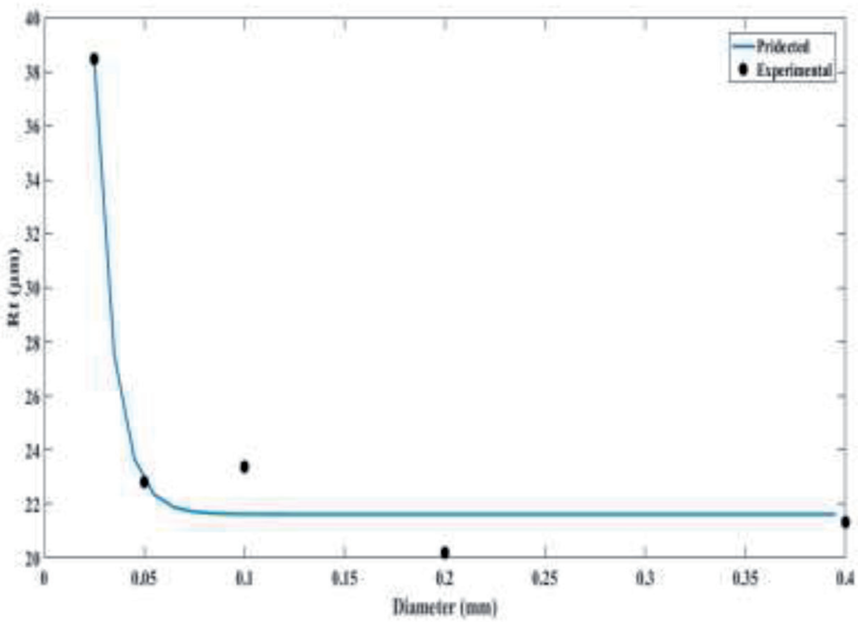


b)

Figure 8.
Experimental and predicted roughness values as a function of the diameter of the workpiece. (a) Ra and (b) Rt for EN AW 2024.



a)



b)

Figure 9.
Experimental and predicted roughness values as a function of the diameter of the workpiece. (a) Ra and (b) Rt for EN AW 2030.

surfaces (Ra and Rt) for EN AW 2024 and EN AW 2030 as one with the representation of prediction models versus the diameter of the workpiece. In all cases, it is observed how the proposed models adjust the range of the experimental values with great approximation.

6. Conclusions

The roughness of machined surfaces is the best indicator of product quality and provides relevant information on their potential for application in different sectors. This work is part of a research on the micro-turning of these materials with the aim of evaluating up to what diameters it is possible to work with conventional finishing tools. Certainly, better behavior is to be expected when specific tools are used for micro-turning. However, low surface roughness values are generally obtained, enabling the specifications of a significant number of practical applications where dimensional accuracy is critical. Among these applications are components and micro-components used in the construction of micromachines (micro-axes, bearing needles, etc.) and, in general, small instrumentation parts, injection systems, etc.

The results obtained allow us to conclude that it is possible to conform by chip removal very small revolution pieces (0.05 mm in diameter) with these alloys, guaranteeing very good surface qualities according to the typical specifications of these applications. It is important to note that the deformation progress used is very low, which has undoubtedly contributed to low roughness values. The use of low values of feed rate and low depths of cut allows cutting forces of very small values in order to guarantee the integrity of the machined workpieces (there is obvious risk of plastic or even fracture if not). On the other hand, the proposed models show very good adjustments as corroborated by the indicators of goodness.

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