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STUDY ON THE APPLICATION LIMITATIONS OF A COLD ROLLING DEVICE FOR INTERNAL CYLINDRICAL SURFACES

BY

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Abstract. Cold surface plastic deformation is an important method for improving the surface quality of parts, offering the advantage of flexibility. This paper presents preliminary research on a device designed for cold surface plastic deformation in order to identify the optimal ranges for specific input parameters. The device used for these processes incorporates rolling elements as deforming components and features a work diameter adjustment mechanism. This mechanism is equipped with a mandrel operated by a screw, which was presented in previous research. To determine the device's working limits, the focus was on obtaining internal cylindrical surfaces with minimal roughness. The cutting speed, feed rate, and processed surface diameter were varied, while the resulting surface roughness and part dimensions were measured.

Keywords: roughness, surface quality, dimensional deviations, rolling, roller-based device.

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1. Introduction

Cold surface plastic deformation is a technological process by which the surface of a part, usually made of metallic material, is improved through plastic deformation without applying external heat (except for the heat generated during the process). This method is used to enhance the wear resistance, hardness, and fatigue resistance of the material without affecting its internal properties, but rather a small surface layer that is sufficient for improving the part's quality.

Cold surface plastic deformation is a current topic of interest and is widely studied internationally. Various procedures can be used for cold surface plastic deformation, such as rolling, vibration rolling, mandrelling, and smoothing. All these procedures rely on a deforming element with specific kinematics in relation to the surface it presses on (Nagîț *et al*., 2017). Franzen et al. investigated the cold surface plastic deformation process, comparing different micro-geometries resulting from processing (Franzen *et al*., 2010). Ziyong et al. worked on rolling the profile of gear teeth using conjugate-shaped tools with axial feed (Ziyong *et al*., 2018), while Qosimova et al. studied the influence of the geometry of the deforming element's tip on the surface quality (Qosimova *et al*., 2021). Youngsik analyzed the influence of hardening tool wear on its machining performance (Youngsik, 2009). Oteny et al. addressed mathematical calculation methods to determine the contact zone between the deforming element and the part (Oteny *et al*., 2017). El-Tayeb et al. researched the behavior and surface quality of cylindrical specimens made of 6061 aluminum alloy after cold surface plastic deformation (El-Tayeb *et al*., 2006).

Several researchers have also focused on developing patents for proposed devices. Clemens, for instance, proposed a device with an adjustment mechanism based on a hydraulic system driven by a screw (Clemens, 1972). Kalen presented a device capable of processing both internal and external surfaces (Kalen, 1973). Ronald et al. developed a combined cutting and hardening device where the work diameter adjustment is done via a screw-nut mechanism (Ronald *et al*., 2002).

For rolling internal cylindrical surfaces, devices with balls, rollers, or diamond spherical tips can be used as deforming elements. Among these, roller-based devices are the most commonly used (Oteny *et al*., 2017), with the working scheme shown in Fig. 1. The specimen is clamped in the lathe chuck and performs the main rotational motion (I). The rolling head is fixed in the tool holder equipped with a Morse taper and performs the feed motion (II), while the rollers execute an auxiliary rotational motion (III). The key geometric parameters influencing the hardening process can also be observed: rolling head diameter (D), rolling depth (t), roller attack angle (α), surface elastic recovery (i), and roller clearance angle (β).

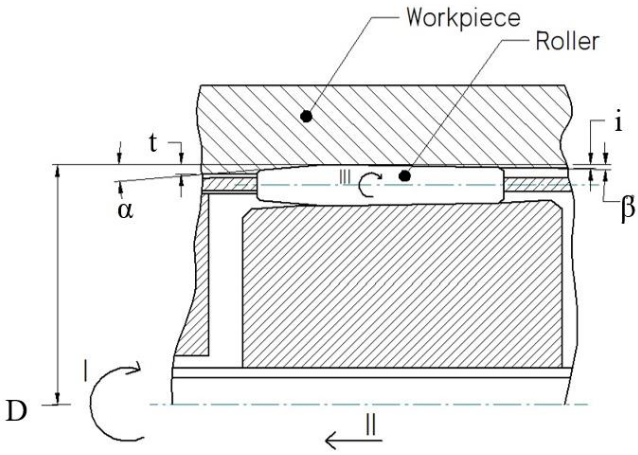


Fig. 1 – Working scheme used for rolling processes.

Based on the working scheme illustrated in Fig. 1, the authors conducted a comprehensive evaluation to identify the most suitable device for surface plastic deformation using multi-criteria decision analysis. This process involved the careful selection and analysis of various alternatives, leading to the identification of a device that was subsequently subjected to a series of preliminary tests. The primary objective of these tests was to validate the device's functionality and application limits under different operating conditions. The study focuses on determining the extent to which specific input parameters–such as working speed, feed rate, and working depth–affect the resulting surface roughness. For this purpose, the experimental setup utilized a hardening head with roller-type deforming elements, which is specifically designed to adjust the working diameter through an integrated adjustment mechanism. This adjustment capability not only enhances the versatility of the device but also allows for more precise control of the deformation process, ultimately influencing the final surface quality. By systematically analyzing these parameters, the research aims to establish optimal working conditions for achieving improved surface characteristics while minimizing defects.

2. Research methodology

The simplified scheme of the rolling head equipped with roller-type deforming elements used for hardening is shown in Fig. 2. Through the working diameter adjusting mechanism, it can process diameters ranging from Ø67 to Ø70 mm. This version of the rolling head proved to be optimal in a previous analysis of several different constructive variants, using an objective analysis method, as mentioned above, a multi-criteria decision analysis method.

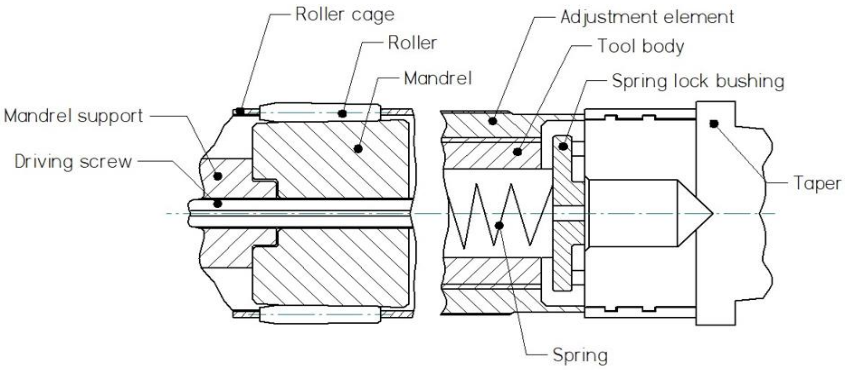


Fig. 2 – Simplified representation of the rolling tool.

The device in Fig. 2 is equipped with roller-type deforming elements mounted in a cage. The rolling head allows the working diameter to be adjusted through a mechanism with a mandrel that presents a threaded bore, operated by a screw. The screw is manually adjusted using a knurled adjustment element for easier handling. The tool also includes safety components such as the mandrel support and a spring lock bushing. Its attachment to the machine tool is done via a Morse taper shank.

The test sample used was a steel alloy 10MoCr20 pipe, graded according to Romanian STAS, with an initial internal diameter of Ø62 mm, a wall thickness of 8 mm, and a length of 1200 mm. The material is a molybdenum-chromium alloy steel, typically used for parts subjected to high loads, such as automotive components or industrial equipment. The chemical composition is presented in Table 1, and the physical and mechanical properties are shown in Table 2 (according to https://www.totalmateria.com).

Table 1
Chemical composition of 10MoCr20

Element	Value [%]
Carbon (C)	0.08 – 0.13
Molybdenum (Mo)	0.25 – 0.35
Chromium (Cr)	1.80 – 2.20

Table 2
Physical and mechanical properties of 10MoCr20

Properties	Value
Density	~ 7.85 g/cm³
Melting point	~ 1450 - 1500°C
Young Modulus	~210 GPa
Hardness	180 - 220 HB
Yield strength (Rp0.2)	~ 500 – 600 MPa

The specimens were cut to a length of 100 mm (the maximum length that can be machined using the lathe tools available in the research laboratory due to the large overhang of the cutting tool). It was then turned from the initial measured diameter of Ø62 mm to the desired diameters for each set of machining operations, ensuring that they fell within the working range of the rolling head.

For the machining trials, the cutting regime used is presented in Table 3.

Table 3

Input parameters used for internal turning

Parameter	Value
Cutting speed (Vc)	86.8 [m/min]
Feed (f)	0.132 [mm/rev]
Cutting depth (ap)	from 0.05 to 2 [mm]

Both the turning process for obtaining the semi-finished parts and the subsequent rolling operations were carried out on a universal lathe SNB 400. These operations were conducted in the Machine Manufacturing Laboratory, Faculty of Machine Manufacturing and Industrial Management, Iaşi, under controlled conditions to ensure consistent results and repeatability of the tests.

Below, Fig. 3a presents the experimental setup, which includes the cylindrical specimen fixed in the lathe's 3-jaw chuck to maintain stability and prevent displacement during the machining process, the hardening tool specifically designed for this type of operation, was mounted in the conical bore of the lathe tailstock quill, which features an internal Morse taper for precise alignment and secure attachment. This configuration ensured accurate positioning and consistent contact between the tool and the sample, which is crucial for achieving the desired surface quality and deformation characteristics.

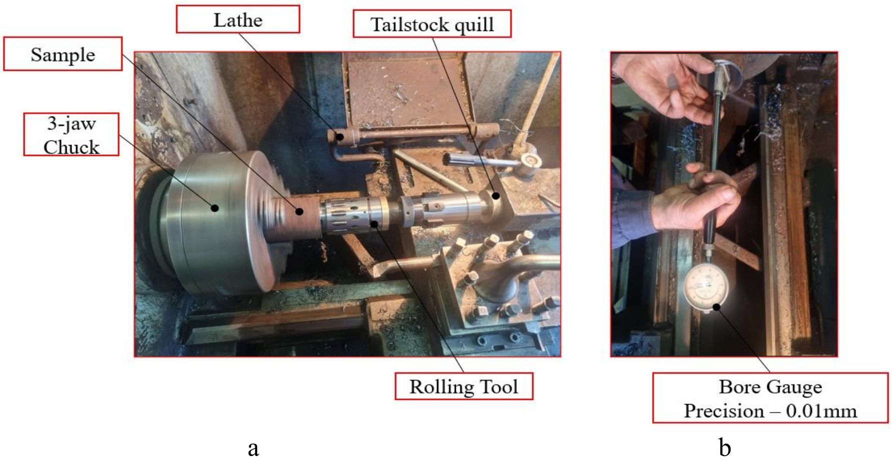


Fig. 3 – a) Setup for the process; b) Final measurements after turning.

For dimensional measurements, after the turning process, a caliper with 0.05 mm accuracy, an external micrometer (50–75 mm) with 0.01 mm accuracy, and a Bore Gauge (50–160 mm) with 0.01 mm accuracy were used (Fig. 3b).

The surface condition was analyzed using a Surtronic S25 roughness tester (Fig. 4). Four measurements were taken for each specimen in opposed locations on the internal diameter, over a length of 4 mm. The measurements provided information about the graphical representation of the surface profile and the roughness parameters Ra and Rz.

Fig. 4 – Surtronic S25 rugosimeter (https://www.taylor-hobson.com/).

3. Experiment Planning

In all three sets of specimens, hardening was performed over a length of approximately 30 mm from the 100 mm-long specimens. The hardened section was then cut from the rest of the sample to allow for the next operation, resulting in three machining operations per specimen. This ensured the same clamping and turning conditions for all three samples (Fig. 5).

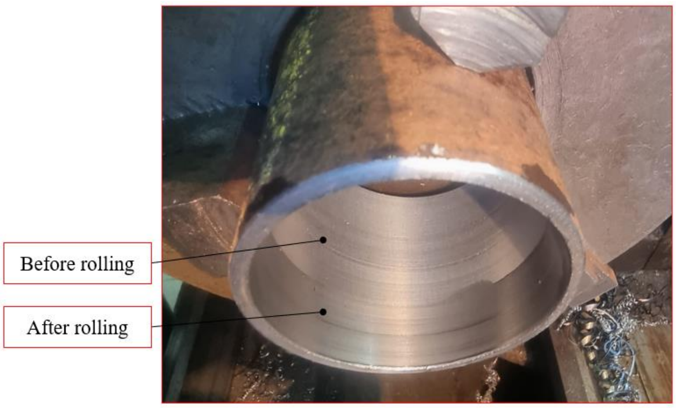


Fig. 5 – Part before and after rolling.

The cold surface plastic deformation operations were performed using a 75W-80 oil-type cooling lubricant specifically formulated for high-pressure applications to ensure effective heat dissipation and reduced friction during the process. Some characteristics are described in Table 4 (TRANSELF NFX SAE 75W - Technical Data Sheet).

Table 4

Characteristic of the lubricant 75W-80 oil-type

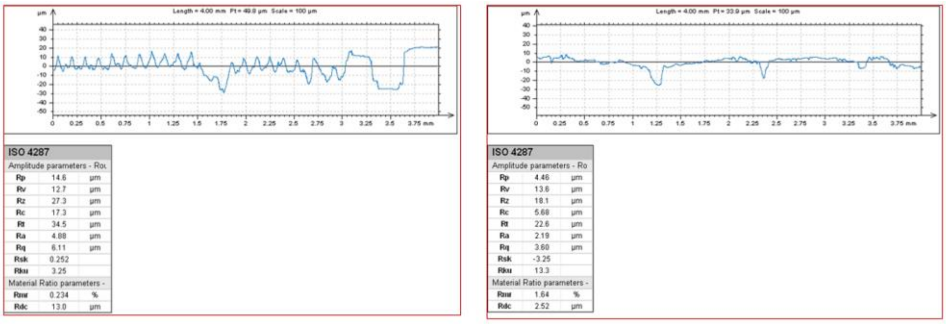
Test	Test Method	Value
Density at 15°C	ASTM D1298	847 [kg/m^3]
Kinetic Viscosity at 40°C	ASTM D445	31 [mm^2/s]
Kinetic Viscosity at 100°C	ASTM D445	6.5 [mm^2/s]
Viscosity index	ASTM D2270	168

Before the rolling operation, the surface roughness after turning was measured at 4.73 µm, expressed as the Ra parameter, which represents the arithmetic mean of the absolute deviations of the surface profile from the mean line over a specified measurement length (according to ISO 4287-1987). This roughness value was obtained as an average of four measurements taken on diametrically opposite surfaces to ensure accuracy and reliability. The individual values recorded were 4.88 µm, 4.04 µm, 5.04 µm, and 4.99 µm, indicating a consistent surface profile with moderate variations.

Figure 6 illustrates the surface profile before and after the rolling process, clearly highlighting the modifications induced by the hardening operation. A distinct contrast can be observed between the hardened zone and the turned-only area, where the initial micro-asperities were significantly reduced through plastic deformation. A comparative analysis of the two surface profiles shows a notable enhancement, with a reduction in surface roughness of approximately 40% after the hardening operation, underscoring the effectiveness of the applied technique.

The roughness profile, measured using a precision roughness tester, exhibited substantial changes after the rolling process, particularly in terms of amplitude reduction. This improvement is most evident in the decrease of the Rz parameter, which is defined by ISO 4287-1987 as the difference between the highest peak and the deepest valley of the surface profile over a reference length. The initial Rz value of 20.2 µm was reduced to 12.9 µm after the process, reflecting a significant decrease in maximum roughness amplitude.

This reduction not only demonstrates the efficiency of the surface hardening process in enhancing surface quality but also serves as a reliable indicator of improved mechanical properties and overall surface integrity.



a b

Fig. 6 – a) Surface's profile measurement, before rolling; b) Surface's profile measurement, after rolling.

The comparison of the machining results focused on the Ra parameter due to its lower sensitivity to fluctuations. In contrast, the Rz parameter, which reflects the difference between the highest peak and the deepest valley, can be significantly influenced by isolated defects such as scratches or local irregularities, resulting in less representative data for overall surface quality analysis.

Three sets of rolling operations were performed, with each set varying a specific parameter: rolling speed, feed rate, and rolling depth. Each set was intended to include six test samples, as follows in Table 5.

Table 5

Input parameters for each set of test samples

Parameter	First set	Second set	Third set
Feed (f) [mm/rev]	0.132	0.029; 0.059; 0.096; 0.151; 0.208; 0.302	0.029
Rolling depth (t) [mm]	0.02	0.02	0.01; 0.025; 0.04; 0.05; 0.06; 0.07
Rolling speed (Vc) [m/min]	21.7; 54.3; 86.8; 108.5; 173.6; 271.3	271.3	271.3

4. Experimental Results

All measurements were taken using the roughness tester mentioned earlier. For each specimen, four measurements were performed on diametrically opposite locations over a length of 4 mm, and the arithmetic mean was calculated to obtain a single value per test sample. This approach helped reduce errors caused by non-uniformities across the entire surface of the specimen.

Table 6 shows the roughness measurement results for the first set of test samples, where the rolling speed was varied. Figure 7 presents the roughness versus rolling speed graph. The constant parameters were a feed rate of 0.132 mm/rev and a rolling depth of 0.02 mm.

Table 6
Roughness measurements, Ra parameter

Part no.	Vc [m/min]	Measure 1 [µm]	Measure 2 [µm]	Measure 3 [µm]	Measure 4 [µm]	Average Roughness [µm]	Improvement [%]
1	21.7	2.25	3.61	2.53	2.63	2.755	71.96
2	54.3	2.68	2.22	2	2.52	2.355	101.17
3	86.8	2.85	3.24	2.93	2.85	2.9675	56.64
4	108.5	16	2.13	2.88	2.72	2.3325	103.10
5	173.6	3.08	3.94	2.96	3.35	33325	42.16
6	271.3	2.87	3.87	3.48	3.72	3.485	35.93

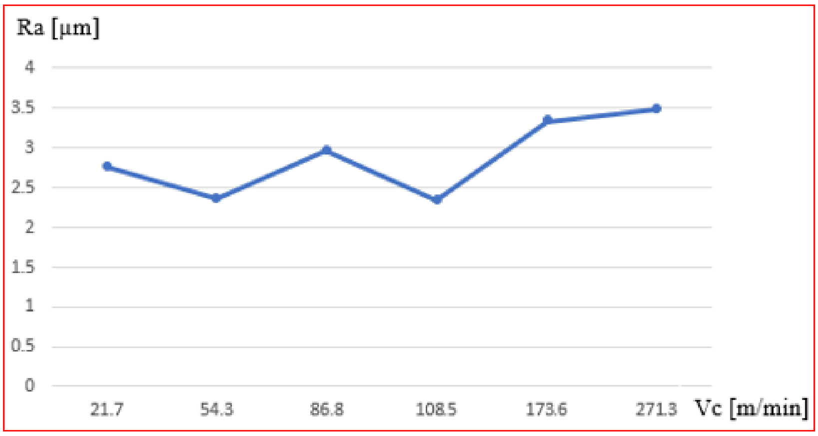


Fig. 7 – The dependence of roughness on rolling speed
(f = 0.132 mm/rev; t = 0.02 mm).

The graph analysis for Fig. 7 reveals fluctuations in roughness values, without indicating a clear trend suggesting a functional relationship between the test sample's rotational speed and surface quality in terms of roughness. The lowest roughness values were recorded at working speeds of 543 and 1085 m/min. This observation suggests the possibility of anomalies in the machining process, necessitating a review of the results through additional experiments. These follow-up tests should be carried out with great attention to eliminate or minimize the identified disruptive factors. If a similar behavior is observed, the speed range analyzed should be narrowed for a more accurate evaluation of a potential dependency relationship.

The roughness measurement results for the second set of test samples, where the feed rate was varied, are shown in Table 7, and the corresponding graph is presented in Fig. 8. The constant parameters were a rolling speed of 271.3 m/min and a rolling depth of 0.02 mm.

Table 7
Roughness measurements, Ra parameter

Part no.	Feed [mm/rev]	Measure 1 [µm]	Measure 2 [µm]	Measure 3 [µm]	Measure 4 [µm]	Average Roughness [µm]	Improvement [%]
1	0.029	2.87	3.87	3.48	3.72	3.485	35.93
2	0.059	3.08	3.94	2.98	3.35	3.3325	42.16
3	0.096	2.68	2.22	2	2.52	2.355	101.16
4	0.151	2.25	3.61	2.53	2.63	2.755	71.96
5	0.208	2.85	3.24	2.93	2.85	2.9675	59.64
6	0.302	1.6	2.13	2.88	1	1.9025	149.01

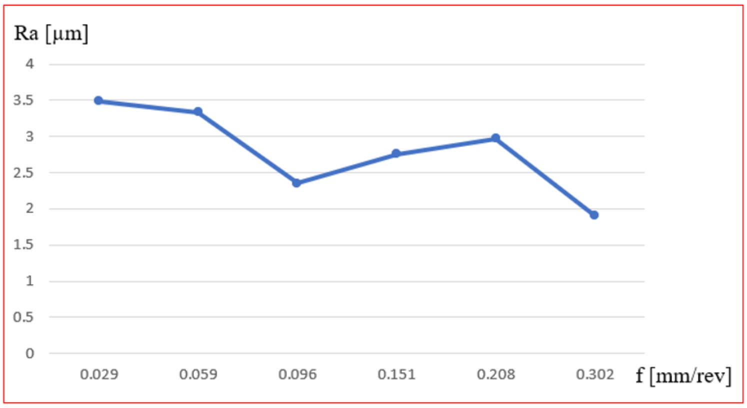


Fig. 8 – The dependence of roughness on rolling feed
(Vc = 271.3 m/min; t = 0.02 mm).

The graph analysis for Fig. 8 shows a significant improvement in roughness for each of the six test samples, with percentage improvements ranging from 35% to 149%. These results demonstrate the benefits of cold surface plastic deformation on the processed surface quality.

However, the graph does not show a clear trend that establishes a precise relationship between the feed rate and the obtained roughness value. Therefore, further research is required to identify and eliminate potential disruptive influences that may have affected the process. These influences could include insufficient system rigidity, tool malfunctions, improper rolling depth, inappropriate rotational speed, human error during measurements, or inadequate or insufficient cooling fluid application. Addressing these factors is necessary for a more accurate and repeatable evaluation of the relationship between machining parameters and the resulting surface quality.

The roughness measurement results for the third set of test samples, where the rolling depth was varied, are presented in Table 8, and the corresponding graph is shown in Fig. 9. The constant parameters were a rolling speed of 271.3 m/min and a feed rate of 0.029 mm/rev.

Table 8
Roughness measurements, Ra parameter

Part no.	Rolling Depth [mm]	Measure 1 [µm]	Measure 2 [µm]	Measure 3 [µm]	Measure 4 [µm]	Average Roughness [µm]	Improvement [%]
1	0.01	2.24	2.33	2.72	1.61	2.225	112.92
2	0.025	1.04	2.02	2.38	1.19	1.6575	185.82
3	0.04	2.19	2.39	2.54	2.41	2.3825	98.84

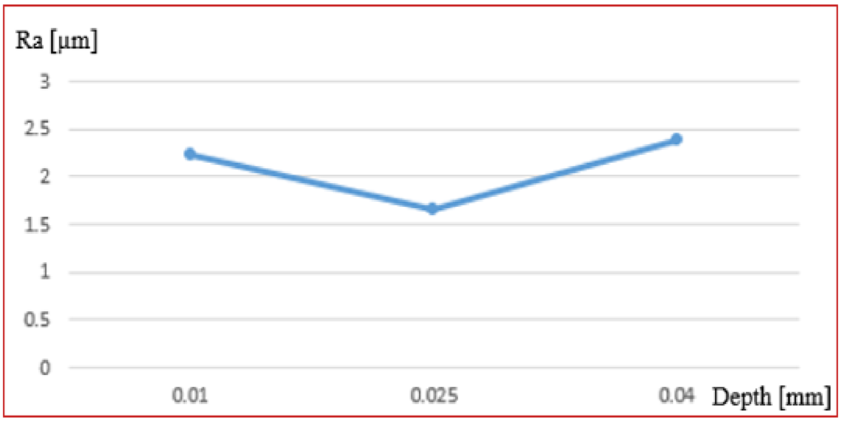


Fig. 9 – The dependence of roughness on rolling depth
(Vc = 271.3 m/min; f = 0.029 mm/rev).

The influence of rolling depth was intended to be tested for six different values, as shown in Table 9, but at a depth of 0.04 mm, the tool holder's rigidity was insufficient, causing the tool to rotate along with the specimens.

The graph in Fig. 9 suggests that a working depth of 0.01 mm is insufficient, resulting in only a minor effect of the processed surface micro geometry. In contrast, a depth of 0.025 mm proved suitable, significantly reducing roughness to approximately 1.5 µm. However, a working depth of 0.04 mm exceeds the system's rigidity limit, causing surface undulations due to vibrations induced by increased machining forces. This conclusion requires further validation through additional experiments to confirm and refine these initial observations.

5. Conclusions

Cold surface plastic deformation resulted in significant improvements in surface roughness, achieving values almost three times lower than the initial roughness. The device used can process internal diameters ranging from Ø67 mm to Ø70 mm, which can be adjusted using the rolling head's adjustment mechanism. The presence of a cooling lubricant is necessary to achieve superior surface quality and reduce the forces involved in the process.

In the final 30 mm of each processed test sample, corresponding to the chuck clamping zones, the rolling process occurred at a greater depth, resulting in more visibly affected surfaces. This implies the need for a clamping device that applies force over a larger surface area or the exclusion of the last test sample where the three jaws were in contact.

Further testing of the device will focus on analyzing surface hardness in the processed layer to determine the influence of the three varying parameters. Additionally, the resulting diameters will be measured to verify elastic recovery relative to the tool's set dimension. A tool holder with significantly higher rigidity will be used in future experiments to allow the study of greater hardening depths than those presented in this paper.

The analyzed device is considered suitable for rolling internal cylindrical surfaces with diameters between Ø67 mm and Ø70 mm, using rotational speeds between 100 and 1250 rev/min (or equivalent speed, measured in m/min) and working depths between 0.01 mm and 0.04 mm. The process quality analysis will be based on experimental planning, statistical analysis of the experimental results, and mathematical models that describe the influence of working parameters on roughness, microhardness, hardened layer thickness, and other parameters resulting from future research.

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STUDIUL ASUPRA LIMITELOR DE UTILIZARE A UNUI DISPOZITIV DE DEFORMARE PLASTICĂ SUPERFICIALĂ LA RECE A SUPRAFEȚELOR CILINDRICE INTERIOARE

(Rezumat)

Deformarea plastică superficială la rece reprezintă o importantă modalitate de îmbunătățire a calității suprafeței pieselor, având avantajul unei flexibilități. Lucrare prezintă cercetări preliminare asupra unui dispozitiv pentru deformare plastică superficială la rece, pentru identificare domeniilor optime de variație a unor parametrii de intrare. Dispozitivul folosit pentru aceste prelucrări utilizează ca elemente deformatoare role și prezintă un mecanism de reglare a diametrului de lucru, prevăzut cu un dorn acționat de către un șurub, ce a fost prezentat într-o cercetare anterioară. În vederea determinării limitelor de lucru ale dispozitivului s-a urmărit obținerea unor suprafețe cilindrice interioare cu rugozități cât mai mici. S-au modificat viteza de prelucrare, avansul de lucru, diametrul suprafeței prelucrate și s-au măsurat rugozitatea și dimensiunea piesei obținute.