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SOME ASPECTS REGARDING THE DESIGN OF TOOLS FOR SUPERFICIAL COLD PLASTIC DEFORMATION OF INTERNAL CYLINDRICAL SURFACES

BY

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Abstract. Surface cold deformation is an alternative to traditional machining processes used for finishing and hardening the surfaces of components in mechanical assemblies. One of the key advantages of cold deformation is that it allows for producing high-quality surfaces using tools mounted on conventional machines–tools commonly found in most mechanical workshops. The resultant surface quality can rival with the one achieved through superfinishing processes, such as finishing grinding or honing. Additionally, this method hardens a sufficiently thick surface layer, enabling the machined parts to function properly without the need for conventional heat treatment. However, specialized tools are necessary for these surface hardening processes, and their proper design is crucial for achieving the desired characteristics in the finished components. This paper proposes an analysis of the different tools utilized for superficial cold plastic deformation of inner cylindrical surfaces, based on logical principles for identifying technical solutions. Using decision support systems (DSS), the adjustment mechanisms for cold surface plastic deformation heads that use roller

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burnishing have been analyzed. Ultimately, this analysis identified a tool that best meets the specified requirements.

Keywords: cold plastic deformation, Multicriteria Decision Analysis (MCDA), rolling tools.

1. Introduction

Cold plastic deformation has been used since ancient times for crafting weapons, tools, and decorative items. Over the centuries, this process evolved with the introduction of mechanically operated machines in the 18th and 19th centuries. By the 20th century, processing methods became more refined, leading to the development of new technologies such as precision wire drawing and rolling, along with the introduction of new materials. Today, this evolution continues with advancements in automation and numerical control, which enable higher precision, increased productivity, and easier control over workpieces.

Cold surface plastic deformation is a mechanical process applied to metallic materials at temperatures below their recrystallization point. This method involves deforming the material to a limited depth beneath the processed surface, without changing its overall shape or subjecting it to high temperatures (Nagîț and Braha, 2000).

Among the various cold plastic deformation processes, can be highlighted rolling, vibratory rolling, burnishing, ultrasonic hardening, and hardening achieved by directing jets of shots, balls, or rollers onto the processed surface. Additionally, smoothing by impact or shock and hardening by centrifuging are included in this category. The working principle of these processes involves applying a specific force to the surface of the workpiece using a tool-deformer whose material is harder than the workpiece material. During the deformation process, both the workpiece and the deforming tool execute various relative movements, as illustrated in Fig. 1. This processing method can be applied to nearly all types of parts, depending on the shape and positioning of the surface being hardened. As a result of these processes, parts can achieve high precision and surface quality that often eliminate the need for additional treatments. Moreover, these surfaces exhibit a characteristic micro-geometry (also referred to as micro-relief) and significant depth hardening of the surface layer. These features provide the processed surfaces, in addition to those resulting from conventional cutting methods, with special characteristics related to wear resistance. This wear resistance arises from both the hardening and the formation of pockets for lubricants in moving joints from which may be the part included.

Based on information from the specialized literature, it can be concluded that the cold surface plastic deformation of internal cylindrical surfaces occurs as depicted in Fig. 1. The main rotational movement (I) is executed by the workpiece, while the feed movement (II) is carried out by the deforming tool. The auxiliary rotational movement (III) is performed by the deforming elements, which simultaneously apply a force (*F*) onto the processed surface. During the deformation process, five characteristic zones can be identified on the surface of the workpiece. The first zone (A) is the base material zone of the workpiece, which does not undergo any physical or mechanical changes during cold hardening. The second zone (B) is the surface layer that experiences modifications after rolling, possessing a micro-geometry resulting from operations prior to cold surface plastic deformation. The third zone (C) is the contact area between the deforming element and the workpiece, where slight deformation initially occurs, followed by plastic deformation. After the deforming element passes over the workpiece surface, a zone characterized by slight elastic recovery (D) will become visible, as the workpiece's surface changes its micro-geometry (zone E), undergoing plastic deformation to a certain depth based on specific working conditions.

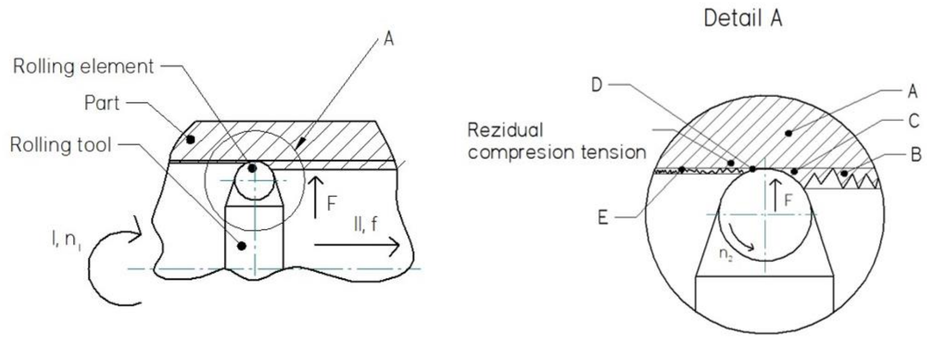

Fig. 1 – Internal rolling process.

Obtaining the desired characteristics for the internal surfaces of cylindrical parts is crucial, especially when these components are used in drilling equipment for oil rigs or as bearings that experience high wear stresses. Therefore, it is essential to design tools that can achieve these characteristics effectively. The existing literature reflects the concerns and contributions of various experts in this field. Botez et al. propose a rolling tool for surface plastic hardening (Botez *et al*., 2017). Nagîț and Braha studied cold surface plastic deformation using diamond spherical tips (Nagîț and Braha, 2000). Oteny et al. discussed mathematical methods for calculating the contact area between the deforming element and the workpiece (Oteny *et al*., 2017). Dogan considers surface plastic deformation as a method for optimizing the manufacturing process of bearing rings (Dogan, 2022), while Qosimova et al. investigated the influence of the geometry of the deforming element's tip on the processed surface (Qosimova *et al*., 2021).

Furthermore, several inventors have developed tools for the cold surface hardening of internal cylindrical surfaces. For instance, Dickinson describes a tool with a hydraulic diameter adjustment mechanism (Dickinson, 1983). Gill proposes a tool with a spring-actuated adjustment mechanism activated by a screw (Gill, 1964). Koppelmann also presents a tool with a similar spring-actuated adjustment mechanism but designed differently (Koppelmann, 1973). Additionally, Steusloff introduces a combined drilling and hardening tool featuring a screw-nut mechanism for diameter adjustment (Steusloff, 1974). Many companies offer tool solutions for rolling processes, such is LMT Fette (www.lmt-tools.com/en/products/rolling-systems).

It is notable that all these tools utilize deforming elements such as rollers, balls, or diamond spherical tips. Among these options, tools using rollers are considered the most effective for the rolling process of internal cylindrical surfaces due to their larger contact area with the workpiece and longer lifespan. Oteny et al. emphasize that the geometry of the rollers, the attack angle, the radius of the spherical tip, and the inclination angle of the rollers are critical factors for the proper design of the tool (Oteny *et al*., 2017).

To implement the working scheme outlined in Fig. 1, specialized tools are necessary. When mounted on universal machine tools, such as a lathe, these tools will facilitate the finishing process of the surfaces. This paper aims to apply principles from multi-criteria decision analysis (MCDA) to identify the requirements the tools must meet and the optimal adjusting mechanism for those requirements. As an objective analysis method, MCDA could conduct the best result for this research.

2. Types of mechanisms for adjusting the working diameter of the tool

The primary components of a tool designed for Cold Surface Plastic Deformation (CSPD) of internal cylindrical surfaces, as outlined in specialized literature, include the following: a clamping and driving shank, which enables the tool to be securely mounted in the machine tool-holder; a tool body, which houses the functional components; deforming elements (e.g., roller- or ball-type) responsible for processing the workpiece surface; a support element (such as a cage) to retain the deforming elements on the tool body; an adjustment mechanism (e.g., mandrel and screw, elastic elements, mandrel and piston, or eccentric mechanisms) for varying the working diameter; safety features; anti-loosening devices; and stiffness-enhancing elements, which contribute to improving the tool's rolling quality.

Among these, the adjustment mechanism for the working diameter plays a pivotal role. It increases tool versatility, reduces production costs, shortens processing times, and simplifies the design process for new tools. Several conceptual solutions for diameter-adjustment mechanisms have been proposed.

One proposed solution involves a hardening tool that utilizes a screw mechanism to control the working depth. In this design, a screw drives a mandrel equipped with an internally threaded bore, which, in turn, pushes the roller-type deforming elements to achieve the desired diameter. The screw mechanism can be operated manually, mechanically, or automatically using stepper motors to ensure high precision.

This approach offers an effective means to achieve adaptability and precision in CSPD tools, facilitating their application across various workpiece geometries and processing requirements.

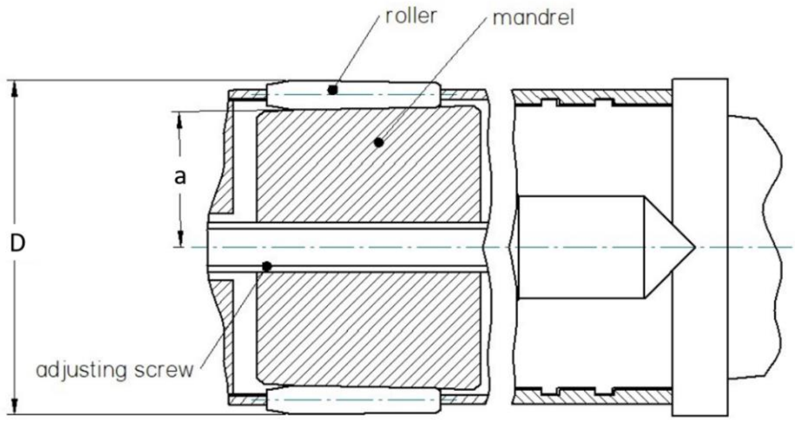

Fig. 2 – Hardening tool with depth adjustment of rollers via a screw.

Furthermore, a different type of tool, which allows working diameter adjustment via a piston—preferably hydraulic due to the high forces involved—is presented in Figure 3. The piston pushes a flange-type driving element, assembled with the mandrel using screws, which then translates the mandrel and adjusts the diameter of the deforming elements.

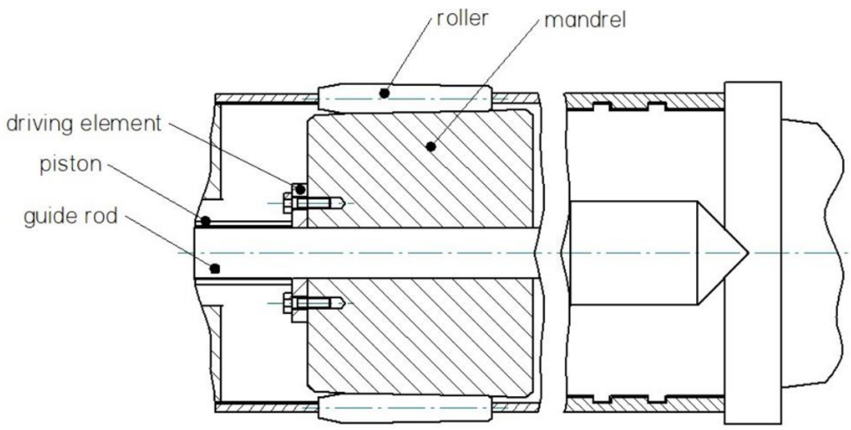

Fig. 3 – Hardening tool with depth adjustment of rollers via a piston.

Another type of tool that can be considered is one that allows adjustment of the working diameter via an eccentric mechanism (Fig. 4). The eccentric receives rotational motion through the driving element, which is fixed to it using screws. By rotating, the eccentric adjusts the working diameter of the rollers. The rotation of the eccentric can be performed manually, mechanically, or automated using stepper motors, which provide very high precision.

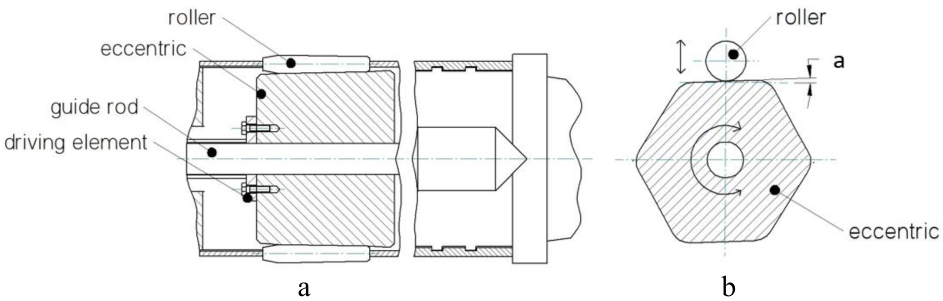

Fig. 4 – a) Hardening tool with depth adjustment of rollers via an eccentric
b) Simplified view with eccentric and roller.

A hardening tool that enables adjustment through a flexible blade mechanism is shown in Fig. 5. The blade can be made from spring steel and is designed to maintain the maximum working diameter for the deforming elements, which can be reduced by tensioning the blade using a piston. The piston decreases the distance between the contact elements and the axis of the tool's body, thereby reducing the roller's working diameter.

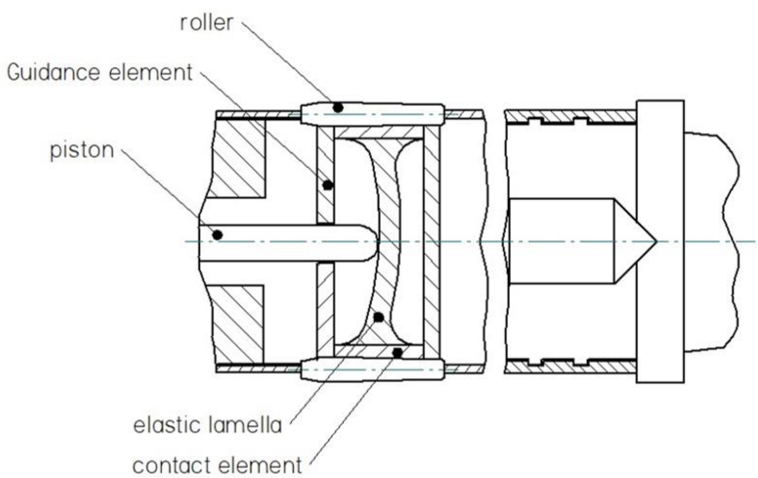

Fig. 5 – Hardening tool with depth adjustment of rollers via an elastic element.

The piston can be operated manually, mechanically (preferably hydraulically due to the high forces involved), or automated via an actuator. To hold the piston in the desired position, a locking element such as a stop pin or a screw-nut mechanism can be used to prevent its displacement under the reactive forces generated by the rollers during cold hardening. The contact elements are maintained in the desired oscillation axis by the guiding element.

It can be observed that the depth adjustment mechanism plays a crucial role, being one of the most significant factors underlying the quality of the rolling tool, due to its degree of versatility, and cost reductions. This mechanism can be designed in various configurations, with a greater or lesser number of components, each offering advantages and disadvantages depending on the application and the criteria it must successfully meet.

3. The application of principles of creative selection of the mechanism for adjusting the working diameter

Multicriteria Decision Analysis (MCDA), also known as Multi-Criteria Decision Making (MCDM), is a decision-support tool designed to assist decision-makers when faced with multiple, often conflicting criteria. Emerging in the 1960s, it was developed to address these conflicts and facilitate transparent compromises. By providing a structured approach, MCDA aims to enhance decision quality through methods that make choices more explicit, rational, and efficient. Its primary goal is to systematically compare options from various perspectives, define objectives, and generate alternatives (Baltazar *et al*., 2013).

According to the information provided above, the following four variants of depth adjustment mechanisms are analysed:

a. Hardening tool with adjustment via a screw;
b. Hardening tool with adjustment via a piston;
c. Hardening tool with adjustment via an eccentric;
d. Hardening tool with adjustment via a flexible element.

After consulting the specialized literature, the following important criteria are considered for the analysis of the variants listed above:

A. To allow adjustment over a wide range of dimensions;
B. To exhibit as high rigidity as possible;
C. To be easily mechanized/automated;
D. To allow adjustment with the highest possible precision;
E. To maintain the desired dimension as accurately as possible.

Calculated numbers of decisions resulted from the establishment of variants of mechanisms and their criteria for analysis:

$$D = C_n^2 = \frac{n \cdot (n-1)}{2} = \frac{5 \cdot (5-1)}{2} = 10, \quad (1)$$

where D – number of decisions, n – number of criteria (Nagîț and Slătineanu, 1998).

In Table 1, all the important criteria are compared two by two, scoring with the following points: 0, 0.5, and 1 for each pair of criteria compared. A score of 0.5 is used when both criteria are of equal importance.

Table 1

Establishing the importance coefficients of the criteria

Criteria	1	2	3	4	5	6	7	8	9	10	Total N	Importance Coef. N/D
A	1	1	0	0.5							2.5	0.25
B	0				0.5	0	1				1.5	0.15
C		0			0.5			0	0.5		1	0.1
D			1			1		1		1	4	0.4
E				0.5			0		0.5	0	1	0.1
TOTAL											10	1

In Table 1, all the important criteria are compared two by two, scoring with the following points: 0, 0.5, and 1 for each pair of criteria compared. A score of 0.5 is used when both criteria are of equal importance.

Next, the criteria are ranked in descending order of importance, based on the calculated importance coefficient (Table 2).

Table 2

Ranks of criteria after analysis

Rank	1	2	3	4	5
Criteria	D	A	B	C	E
Importance Coef.	K_D=0.4	K_A=0.25	K_B=0.15	K_C=0.10	K_E=0.10

It follows that the most important characteristic that the mechanism must fulfill is the ability to allow the most precise adjustment of the working depth. However, special attention must also be given to the possibility of having a wide range of dimensions at which it can be adjusted.

The next step consists of comparing the proposed solutions for the diameter adjustment mechanisms, two by two, based on each evaluation criterion, also using the calculated importance coefficient. This is carried out in Table 3:

Table 3
Comparison of representative solutions

Solution	1	2	3	4	5	6	D_i	N_{vi}
	Criterion A						D_A	$(K_A/6)\cdot D_A$
a	0.5	1	1				2.5	0.10416
b	0.5			0.5	0.5		1.5	0.0625
c		0		0.5		0.5	1	0.0416
d			0		0.5	0.5	1	0.0416
	Criterion B						D_B	$(K_B/6)\cdot D_B$
a	1	0.5	1				2.5	0.0625
b	0			0	1		1	0.025
c		0.5		1		1	2.5	0.0625
d			0		0	0	0	0.000
	Criterion C						D_C	$(K_C/6)\cdot D_C$
a	0	0.5	0				0.5	0.0083
b	1			1	0.5		2.5	0.04166
c		0.5		0		0	0.5	0.0083
d			1		0.5	1	2.5	0.04166
	Criterion D						D_D	$(K_D/6)\cdot D_D$
a	1	1	1				3	0.2
b	0			0.5	0.5		1	0.0667
c		0		0.5		0	0.5	0.0333
d			0		0.5	1	1.5	0.100
	Criterion E						D_E	$(K_E/6)\cdot D_E$
a	1	1	1				3	0.050
b	0			1	1		2	0.0333
c		0		0		0.5	0.5	0.0083
d			0		0	0.5	0.5	0.0083

Following the calculations, in this case, the summation of the results for each diameter adjustment mechanism analyzed based on each evaluation criterion, the following values result:

$$N_{Va}= 0.10416 + 0.0625 + 0.0083 + 0.2 + 0.05 = 0.4249 \quad (2)$$

$$N_{Vb}= 0.0625 + 0.025 + 0.04166 + 0.0667 + 0.0333 = 0.2291 \quad (3)$$

$$N_{Vc}= 0.050 + 0.0625 + 0.0125 + 0.0333 + 0.0083 = 0.1666 \quad (4)$$

$$N_{Vd}= 0.04166 + 0.000 + 0.04166 + 0.100 + 0.0083 = 0.1915 \quad (5)$$

Verification of the correctness of the calculations is made by equalizing the sum of the values calculated above with 1:

$$N_{Va} + N_{Vb} + N_{Vc} + N_{Vd} = 0.4249 + 0.2291 + 0.1666 + 0.1915 = 1 \quad (6)$$

Next, in Table 4, the results have been ranked in descending order based on the values obtained from the calculations:

Table 4
Ranks of the solutions

Rank	1	2	3	4
Solution	a	b	d	c
Value	0.4249	0.2291	0.1915	0.1666

As shown in Table 4, the optimal solution for this research is solution a: a hardening tool with adjustment via a screw. By operating the screw, it further translates the mandrel, which has a threaded inner hole. The inclined outer surface causes the diameter of the rollers to increase or decrease. The tool presents self-locking due to the thread, which inherently fulfills this requirement, enabling a very high precision adjustment (depending only on the thread pitch, which should be as fine as possible). Solution A is recommended as suitable for criteria A, B, D, and E, but it is not recommended for criterion C, as it is difficult to mechanize, although it can be automated using an electric motor.

4. Conclusions

Designing a surface cold plastic hardening tool requires significant effort and careful attention to numerous details. Since this process operates at depths of only a few hundredths of a millimeter, the precision of the component elements–particularly the adjustment mechanisms–and the accuracy of the machining prior to hardening are crucial for achieving the desired results in the hardening process. The components of the adjustment mechanism must be designed to provide precise control over the hardening depth. This adjustment is critical for compensating for any deviations from the desired nominal diameter that may occur during previous operations, typically turning. Moreover, the tool's versatility increases with the range of sizes it can accommodate and the level of precision at which it can be set. Additionally, the rigidity of the tool must be exceptionally high to maintain the set dimensions and minimize the impact of vibrations and non-uniformities.

In conclusion, the optimal mechanism identified to meet these requirements uses a mandrel adjustment driven by a screw. Future studies may explore alternative mechanisms that could offer additional advantages.

Furthermore, opportunities to optimize the currently identified solution or to implement easier automation methods should be investigated. Lastly, studying the effects of rolling speed (workpiece rotation speed), feed rate, and cutting depth on the quality of the resulting surface–such as roughness, hardness, shape deviations, and discrepancies from the nominal diameter (including elastic recovery)–could also provide valuable insights.

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ASPECTE PRIVIND PROIECTAREA SCULELOR PENTRU DEFORMARE PLASTICĂ SUPERFICIALĂ LA RECE A SUPRAFEȚELOR CILINDRICE INTERIOARE

(Rezumat)

Prelucrarea prin deformare plastică superficială la rece reprezintă o alternativă a prelucrărilor prin aşchiere, aplicată componentelor din ansamblurile mecanice, în scopul finisării şi durificării suprafețelor supuse unor solicitări intense în timpul funcţionării. Avantajul acestor tipuri de prelucrări este reprezentat, printre altele, de posibilitatea obținerii cu ajutorul unor dispozitive montate pe mașini – unelte clasice existente în majoritatea atelierelor mecanice, a unor suprafețe a căror calitate corespunde cu cele obținute prin operații de superfinisare prin aşchiere (rectificare de finisare sau chiar

honuire). Concomitent cu aceasta, are loc și durificarea unui strat cu grosime suficient de mare, încât să permită buna funcționare a pieselor astfel prelucrate, fără a fi necesar să fie supuse unui tratament termic clasic.

Pentru realizarea unor asemenea prelucrări, sunt necesare însă dispozitive speciale, a căror proiectare corectă, asigură premisele obținerii unor piese cu caracteristicile dorite. Lucrarea de față propune, pe baza aplicării unor principii logice de identificare a soluțiilor tehnice, o analiză a variantelor de dispozitive utilizate în prelucrarea prin deformare plastică superficială la rece a suprafețelor cilindrice interioare. Aplicând Analiza valorii și Tehnica deciziei impuse au fost analizate mecanismele de reglare a capetelor de prelucrare prin deformare plastică superficială la rece prin rulare cu role și a fost identificat un dispozitiv care corespunde cel mai bine cerințelor impuse.