Vyacheslav Aleksandrovich Golenkov
Sergey Yuryevich Radchenko
Daniil Olegovich Dorokhov

Theory and Technology of Roll Stamping

Springer

Theory and Technology of Roll Stamping

Vyacheslav Aleksandrovich Golenkov ·
Sergey Yuryevich Radchenko ·
Daniil Olegovich Dorokhov

Theory and Technology of Roll Stamping

Springer

Vyacheslav Aleksandrovich Golenkov
Orel State University named after I. S. Turgenev
Orel, The Oryol Area, Russia

Sergey Yuryevich Radchenko
Orel State University named after I. S. Turgenev
Orel, The Oryol Area, Russia

Daniil Olegovich Dorokhov
Orel State University named after I. S. Turgenev
Orel, The Oryol Area, Russia

ISBN 978-3-030-91816-3 ISBN 978-3-030-91817-0 (eBook)
https://doi.org/10.1007/978-3-030-91817-0

Translation from the Russian language edition: Теория и технология валковой штамповки © Оружие и технологии 2019. Published by Оружие и технологии. All Rights Reserved.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Introduction

Production of competitive equipment for various purposes requires parts with high mechanical and physical properties, technologically simple in production and economically feasible.

Fundamentally, new metal forming processes include a technology with complex local loading of the workpiece plastic deformation zone, which simultaneously combines bulk stamping and local deformation of the deformation zone by spinning rollers or driven rolls, called "roll stamping."

The main objective of developing a new method and corresponding technology is to provide control over the plastic deformation process and obtain products with predetermined technological and physical properties. Roll stamping allows to significantly reduce the deformation force, increase the tool service life, increases the metal utilization rate, reduce or completely eliminate the need for subsequent machining, and decrease metal and energy consumption of equipment.

One of the important advantages of the new production process is the controlled gradient hardening of the subsurface layers of the product due to periodic local loading of the deformation zone with the simultaneous application of a global monotonic load. This allows to form submicro- and nanostructures gradient starting from the outer surface, while the values and distribution of mechanical properties over the volume of the product can be planned in advance.

The existing techniques for calculating local deformation processes, as well as techniques for calculating traditional bulk stamping methods with a fixed region of deforming force application (pressing, extrusion, upsetting, etc.), do not allow calculating the processes of roll stamping with a sufficient accuracy. This monograph discusses the roll stamping theory basics, research of production processes, as well as methods for their design.

The following researchers from the Oryol State University named after I. S. Turgenev took part in the preparation of the materials for this publication: P. G. Morev, K. I. Kapyrin, G. P. Korotky, T. V. Fedorov, I. M. Gryadunov.

Contents

1 Analysis of Methods for the Production of Axisymmetric Parts with Given Specifications 1
1.1 Workpiece Forming Methods and Their Effects on the Mechanical and Physical Properties of Metals 1
1.2 Classification of Roll Stamping Processes 9
1.3 Hardening by Metal Forming Methods 12
References 22

2 Development of the Calculation Procedure for Production Processes of Metal Forming 29
2.1 Traditional Methods of Metal Forming Process Calculation 29
2.2 Mathematical Problem Definition for Metal Forming 31
2.3 Solving Problems of Elastoplastic Deformation by the Finite Element Method 33
2.3.1 Calculation of Temperature Fields 33
2.3.2 Calculation of Displacements, Deformations and Stresses 36
2.4 Accuracy Estimation Algorithms 37
2.4.1 Results Accuracy Estimation 37
2.4.2 Posterior Estimates Based on the Duality Method 37
2.4.3 Posterior Estimates Based on Calculations Using Grids of Different Densities 42
2.5 Defining a Finite Element Grid 46
2.6 Main Aspects of the Numerical Solution of MF Problems 48
2.7 Analysis of Elastoplastic Models Using Dedicated Software Packages 54
References 54

3 Roll Stamping of Long Bar Stock 57
3.1 Analysis of the Stress–Strain State During Roll Stamping of a Strand-Shaped Workpiece 57
3.2 Experimental Studies of Roll Stamping of Long Bar Stock 63

3.3 Long Bar Stock Roll Stamping Process Refinement 77
References 82

4 Roll Stamping of Piece Blanks 85
4.1 Metal Flow Specifics During Roll Stamping 85
4.2 Neutral Cross-sectional Angle and Roll Stamping Process Kinematics 88
4.3 Conditions and Specifics of Workpiece Axial Tightening During Roll Stamping 91
References 94

5 Force Parameters of Roll Stamping 95
5.1 Roll Stamping Stages, Analysis of Changes in Working load, and Factors Affecting the Force Parameters of the Deformation Process 95
5.2 Influence of the Relative Deformation Rate on the Workpiece Rotation Condition 100
References 102

6 Mathematical Modeling of Roll Stamping 103
6.1 Main Objectives and Solution Methods 103
6.2 The Procedure for Calculating Tool Loads During Roll Stamping 104
6.3 Calculation of Roll Stamping Process Parameters During the Piercing Stage 104
6.4 Calculation of Roll Stamping Process Parameters at Roll Burnishing Stage 115
6.5 Stress and Deformation Distribution in the Workpiece Cross Section at the Roll Burnishing Stage 128
6.6 Calculation of the Roller Force and Contact Stress, Punch Force, Required and Created Moments 130
6.7 Methodology for Calculating the Maximum Permissible Relative Workpiece Deformation Rate 140
6.8 Distribution of Normal Stresses on the Tool During Roll Stamping 142
References 147

7 Main Production Processes of Roll Stamping 149
Reference 157

8 Local Strain Hardening 159
8.1 Problem Definition 159
8.2 Calculation of Kinematic and Force Parameters of Roll Burnishing 160
8.3 Mathematical Modeling of Roll Burnishing 168
8.4 Experimental Studies of Roll Burnishing 173
References 175

9 Hardening by Complex Local Deformation 177
9.1 Roll Burnishing with Braking Torque 177
9.1.1 The Effect of the Braking Force Applied to the Roller on the Deformation Rate 178
9.1.2 Multi-cycle Roll Burnishing 183
9.2 Roll Burnishing with Forming and Smoothing Tools 192
9.3 Analysis of the Results of Study of the Forming Tool Shape and Geometry for Hardening by Complex Local Loading of the Deformation Zone 201
9.4 Mathematical Modeling of Complex Local Deformation 204
9.5 Justification of Odqvist Parameter as the Generic Criterion for Comparing Physical and Mathematical Modeling Results 214
9.6 Influence of the Forming Tool Geometry and Its Indentation Depth on the Stress–Strain State of the Workpiece in a Single Act of Deformation 220
9.7 Influence of Axial Compression on the Stress–Strain State of the Workpiece During Hardening by Complex Local Loading of the Deformation Zone 233
9.8 Study of the Influence of Process Conditions on the Processes of Hardening by Complex Local Loading of the Deformation Zone 241
References 254

10 Complex Local Deformation Processes and Methods of Their Design 259
10.1 Classification of Complex Local Deformation Processes 259
10.2 Workflow Processes of Complex Local Deformation by Roll Burnishing 262
10.3 Methodology for Designing MF Methods Based on Complex Local Loading of the Deformation Zone 270
10.3.1 Determining Parameters of Roll Burnishing with Braking Torque 270
10.4 Methodology for Designing Roll Burnishing Processes with Forming and Smoothing Tools Using the Odqvist Parameter 275
10.4.1 Problem Definition for Design of Metal Forming Processes with Complex Local Loading of the Deformation Zone, Allowing Formation of Gradient-Hardened Structures in Metals and Alloys in a Controlled Manner 275

10.4.2 Recommendations for the Selection of Process Parameters in the Design of Metal Forming Methods with Complex Local Loading of the Deformation Zone, Allowing Forming Gradient-Hardened Structures in Metals and Alloys in a Controlled Manner 278
10.5 New Processes of Hardening by Complex Local Loading of the Deformation Zone 297
10.5.1 The Process of Hardening by Complex Loading of the Deformation Zone to Obtain Various Mechanical Properties Along the Workpiece Length 297
10.5.2 The Process of Hardening by Complex Loading of the Deformation Zone for Forming Using Various Tools in a Single Processing Cycle 298
References 299

Chapter 1
Analysis of Methods for the Production of Axisymmetric Parts with Given Specifications

1.1 Workpiece Forming Methods and Their Effects on the Mechanical and Physical Properties of Metals

Axisymmetric parts having a stepped outer and inner surface, long body, external or internal thread are widely used due to the most efficient distribution of inner load stresses and the minimum amount of materials needed for their production.

Production version selection is based on the part production accuracy, production program, design complexity, workpiece and part geometric dimensions, material composition, capabilities of the available equipment, as well as degrees of scientific validity, development, and experimental testing of the selected production process. Technology selection is mostly based on the final product requirements and its operation specifics.

Axisymmetric part production technology includes cutting and forming processes.

For parts with high-quality requirements, cutting has the following main disadvantages: low metal utilization rate (0.2…0.6), low performance, as well as the inability to improve mechanical and physical properties of parts.

While metal forming processes (MF) benefit from work hardening, absence of cuts, macrostructure improvement, as well as metal utilization rate increase up to 0.8 and higher. The following main MF processes are utilized [1–3]:

- forging, stamping with drop hammers and hydraulic presses;
- hot stamping with hot-stamping crank presses (HSCP) and horizontal forging machines (HFM);
- bulk cold stamping;
- cross-wedge and cross-helical rolling.

Forging [4, 5] produces high-quality large workpieces for further processing. Forging is one of the most efficient ways to obtain high-quality workpieces in a dedicated production and the only possible way to obtain large workpieces.

V. A. Golenkov et al., *Theory and Technology of Roll Stamping*,
https://doi.org/10.1007/978-3-030-91817-0_1

However, forging is almost not used in the instrument making (low weight parts) due to the low geometric accuracy of the products obtained, which requires significant finishing and increased metal consumption, as well as relatively low performance.

Hot stamping [6, 7] is widely used as well due to its advantages over forging, namely

- higher performance;
- stamped products have significantly smaller allowances and tolerances, reducing metal consumption.

The disadvantages of bulk hot stamping are higher deformation forces compared to forging, as the entire product is simultaneously deformed and metal flow is restricted by the die cavity walls during hot stamping.

Furthermore, heating a workpiece, especially a small one, induces such surface phenomena as scale formation, decarburization, and metal expulsion, leading to a significant quality decrease of the obtained forgings and the need for subsequent cutting.

Thus, the discussed class of parts can be produced by bulk cold stamping [8–11] in the most efficient way. Bulk cold stamping with cold stamping machines, as well as rotary and rotary conveyor lines, is successfully used to produce a wide range of generic parts (fasteners, sleeves, etc.); however, in small-scale production, such equipment is not always economically feasible due to the high labor intensity of tool manufacturing and long duration of equipment changeover. Furthermore, this type of equipment complicates the production of parts with complex stepped lateral surfaces, as well as parts with high thin walls (which are manufactured via reverse extrusion) due to very significant deformation forces and short tool life.

The application scope of bulk cold stamping can be expanded by improving the properties and achieving more complicated shapes of stamped parts. The technology for the production of axisymmetric parts with stepped outer and inner surfaces can be significantly improved by combining bulk cold stamping with other types of cold working—special types of metalworking with local loading, in particular, cross-wedge and helical rolling, and shape rolling.

During cross-wedge rolling [12], the workpiece is deformed by a pair of wedge tools, which advance the deformation zone along the workpiece axis as they move according to the angle of inclination of the deforming wedges. The workpiece is rotated by the tool longitudinally and perpendicular to the movement of the wedges. The deformed workpiece section diameter decreases, and its length increases as it is drafted and rolled by the inclined tool edges. Cross-wedge rolling can produce stepped shaft-like products with various surface shapes, having longitudinal and transverse grooves, as well as sharp and smooth transitions between steps. Product dimensions are limited by the equipment capabilities and generally do not exceed 100 mm in diameter and 800 mm in length when processing separate workpieces.

The cross-wedge rolling produces precise products of final size or with grinding allowances. For instance, tolerance for diameters below 30 mm can be as low as ± 0.1 mm and for diameters up to 100 mm— ± 0.4 mm. However, the requirements for tools, technology, and equipment to achieve such accuracy are high and often unreachable. Therefore, outer surfaces of workpieces obtained by wedge rolling are usually machined on lathes.

Another disadvantage is the impossibility of creating holes in parts. Furthermore, the idle run of a flat wedge tool reduces the rolling process performance compared to other rolling methods, while the limited travel of the deforming wedges narrows the technological capabilities of the process.

During helical rolling [13–15], various sections of long bar stock are sequentially drafted while traveling through screw roll grooves. Thus, a periodic circular profile is formed. In addition to shaped periodic profiles, balls, and cylindrical workpieces, helical rolling allows producing ring and sleeve products shaped on the outer diameter of the pipe. Ring and sleeve products are produced from bar stock, which is pierced on a piercing mill first. Rolling allows obtaining piece goods.

However, the produced part may have various defects—first of all, shrinkage cavities on sides and axial porosity, as well as transverse and longitudinal backfins, and spiral ridges. The disadvantage of this hollow stepped part production method is the need to use different equipment types, which increases the production time and cost, as well as the cost of designing and manufacturing of working roll dies.

During cold shape rolling [16], workpieces are shaped with a rotating punch, and the axis of its rotation is located at an angle to the workpiece rotation axis.

Specifics of workpiece forming during shape rolling, the possibility of workpiece structure stability loss, as well as ultimate material deformation, which can be achieved under conditions of local deformation, all this limit the technological capabilities of cold shape rolling for the production of flanged parts. The disadvantage of this method is the need to use tube workpieces for the production of hollow parts [17].

Production of axisymmetric hollow stepped parts is associated with labor-intensive production processes, which are characterized by certain disadvantages such as high deformation forces requiring equipment with large dimensions and power, high metal consumption, short tool life, long production cycle, as well as the high cost of the resulting products.

A common disadvantage of the methods described above is the impossibility of producing parts having both holes and a stepped outer surface. Therefore, the challenge of developing fundamentally new technologies and equipment, which can compete on the world market, allowing to obtain high-quality products at the lowest production cost is currently relevant.

Generally, variable cross-sectional products (VCSP) are round-shaped parts (or workpieces) with a variable cross-sectional area or wall thickness along their axis. Such products are used in various industries. Most commonly, these are elements of load-bearing structures, the shape, and dimensions of which must satisfy the relative maximum functional strength at minimum material consumption. Products with local wall thickenings are a special case of VCSP.

Local wall thickenings in VCSP serve various purposes [18]. They are used as follows:

- compensation means for weak spots in mechanical or welded joints;

- structural elements for local reinforcement;
- structural elements for increasing the contact area in friction joints, as well as in permanent joints.

In some cases, additional requirements for endurance, wear resistance, reliability, and guaranteed service life are imposed on VCPS [19].

VCSPs in the form of tubular products [20] are the most widely spread and can be conditionally divided into the following types:

- having variable diameter and constant wall thickness;
- having variable wall thickness and constant outer diameter;
- having variable diameter and wall thickness;
- with a constant inner diameter and a barrel in the butt or middle section.

The later VCSP type includes such products as spars—bearing elements of blades. One of the intermediate stages of spar production, consisting of more than 200 operations, is a workpiece in a form of 6–6.5-m-long ø273 × 24 mm hot-rolled pipe made of 40XH2MA-Ш steel having butt barrel with a diameter of 335 mm over a length of at least 250 mm.

It is obvious that producing such parts by cutting is not feasible due to a high amount of wasted metal in the form of chips, as well as the resulting metal structure having cut fibers [18].

Centrifugal casting or investment casting cannot be used as well due to low mechanical properties of the resulting product having discontinuities, fluctuations, and deviations of a strictly regulated chemical composition, which is unacceptable for such critical parts as spars.

Thus, the only possible methods for obtaining such products are widely used pressure forming methods, such as transverse, cross-wedge, and helical rolling on three-high or rotary rolling mills [12–15]. In this case, the barrel is located in the unrolled section of the workpiece. However, this method leaves the metal structure of the barrel untouched.

During blanking [18, 21–24], a section of the workpiece is extruded through the die, followed by the reverse extraction of the product. Compared to other processes, blanking (extrusion) improves the metal structure and mechanical properties; however, extrusion of products with an outer diameter exceeding 250 mm with a 3–fourfold thickening of the wall is currently an almost insoluble task due to significant deformation forces.

The same reasons as in blanking render useless rotary rolling [25–28], reduction [29], and some other processes [20, 30–32].

The most widespread and efficient ways to obtain barrels on long-axis workpieces are by upsetting the end part from metal edging into the butt [6]. Such processes can be classified into three categories according to the deformed area heating method.

The *first category* includes processes in which heating is performed outside the deformation zone, and heated workpieces are transferred into the die cavity. Operations in this category are performed using horizontal hydraulic presses [33–35] or horizontal forging machines (HFM) [36, 37], with upsetting done in dies in several passes. However, this technology can be efficiently used only for stamping products with an outer diameter of 50–150 mm, while upsetting a barrel on a spar workpiece from a pipe with a diameter of 273 × 24 mm to an outer diameter of 350–360 mm with a barrel length of 250–300 mm requires a 4–5-pass technology with intermediate heating [6], which leads to microstructure deterioration and chemical composition instability for alloyed steel 40XH2MA-Ш [38]. Furthermore, it was proved [39–41] that regardless of the upsetting process and route, workpiece walls first undergo plastic bending at HFM with the formation of folds, which are subsequently stamped out forming fiber bends. Studies of the effects of fibrous structure [29–31] on the product quality have unambiguous results, but it is traditionally believed that fiber bends negatively affect such mechanical properties of the material as endurance, impact strength, and plasticity.

Upsetting in dies using hydraulic presses by its technological properties differs from upsetting in HFM by a lower travel velocity of the deforming tool; therefore, it retains all the disadvantages inherent to upsetting in HFM, which means this equipment cannot be used to produce spar workpieces.

The *second category* includes certain processes, which use machines with unconventional design [42–69]. Analysis of each of these devices leads to a general conclusion—none of the proposed designs allow producing desired products with given quality and performance parameters.

Finally, the *third category* of processes based on continuous-incremental machines, for example, electrical upsetting machines, [70, 71] is the most promising for spar workpiece production. The processes occurring in workpieces during electrical upsetting have been studied quite well [72, 73], the stress–strain state of metal at electrocontact heating has been studied, and the fundamentals of technology and equipment for its implementation have been developed. However, the equipment described in the reference sources allows obtaining barrels of a very limited length on pipes with a maximum diameter below 100 mm [74]. The appropriate technologies and equipment shall be developed to obtain large barrels with an outer diameter of up to 360 mm using the electrical upsetting technology.

The most promising and actively developed in recent years are MF processes for the production of products using methods of local action of the tool on the material. The common distinctive feature of all these methods is that at each moment the workpiece is not formed in its entire volume, but in one or several local zones that travel over time along the volume of the product. Forging operations of broaching and rolling, as well as the relatively recent technology of continuous-incremental upsetting with induction heating of the plastic deformation zone, [75, 76] are considered conventional in this technology area.

In particular, the barrel is deformed over the entire prepared length of the pipe workpiece not immediately, but gradually, by sequentially enlarging the barrel providing a continuous plastic flow of metal of the original pipe workpiece into the barrel through the deformation zone heated to forging temperature. The deformation magnitude and, consequently, the wall thickening ratio depend on the ratio of metal flow velocity entering the plastic zone and exiting from it. For instance, in

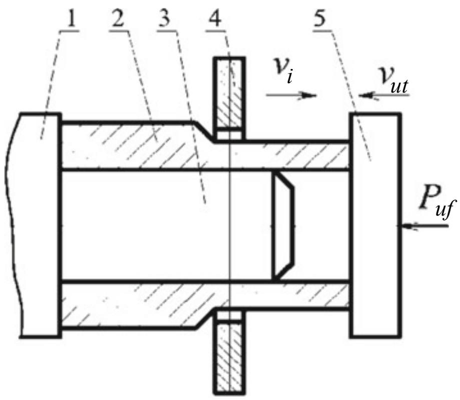

Fig. 1.1 Diagram of continuous-incremental pipe upsetting with HFC eating and counter motion of the upsetting tool and inductor: *1*–stop; *2*–workpiece; *3*–insert; *4*–inductor; *5*–upsetting tool; v_i–inductor table velocity; v_{ut}–upsetting tool velocity; P_{uf}–upsetting force

case of the counter direction of travel (Fig. 1.1), the upsetting ratio is determined by the ratio of v_{ut} upsetting tool velocity and v_i heating device (inductor) velocity.

Besides the counter-directional process, a unidirectional upsetting process is also used, which, however, has a significant disadvantage, since it requires a much larger travel distance for the moving parts of the press for obtaining barrels of the same length.

The continuous-incremental upsetting of VCSP has several advantages:

- allows upsetting "long" barrels, when the length is limited only by equipment capabilities;
- allows obtaining barrels with an upsetting ratio of up to 3.5–4;
- allows forming barrels without loss of stability in the deformation zone, i.e., obtaining macrostructures without fiber jams and bends.

Continuous-incremental upsetting with HFC heating requires significantly less operating forces, which allows obtaining butts on pipes with a diameter of up to 400 mm, and by switching to a lower frequency—even larger diameter, since the depth of current penetration during HFC heating is determined by the empirical dependence [77]:

$$\Delta = 600/\sqrt{f} \tag{1.1}$$

where

Δ is current penetration depth into steel during induction heating;
f is current frequency, Hz.

The first advances in the technology [78] and equipment [79] of continuous-incremental upsetting date back to the end of the 50s of the XX century. At that time, the author of the technology V. Ya. Milgevsky carried out multiple experiments and developed some empirical recommendations for the selection of inductor parameters and power parameters of the process [75, 76]. However, for a long time, the continuous-incremental method of pipe upsetting using HFC heating did not become widespread, primarily due to the lack of a satisfactory theoretical study of the processes occurring during upsetting and justification of the choice of technological parameters of power and heating equipment.

A very limited number of studies are devoted to the process of continuous-successive upsetting of pipes with HFC heating, and most of them consider experimental processing and industrial implementation of the developed technology in relation to specific products [75, 76].

The first theoretical studies devoted to the analysis of the processes occurring during continuous-incremental upsetting revealed unsteadiness of plastic flow of metal in the deformation zone caused by significant temperature variations and, consequently, variations of plastic properties of metal along the deformation zone [18, 80]. This phenomenon explains the mechanism of plastic flow of metal into the thickened butt part at a gradual wall thickness increase in the deformation zone when material travel is not limited by the tool. Thus, the geometry of the free surface of the deformation zone during upsetting of a pipe blank depends on the distribution of plastic properties over the deformation zone.

The problem of deformation resistance distribution during upsetting of thin-walled pipes was first solved by M. N. Gorbunov based on the condition of a linear stress state, plane deformation, and a linear variation of the wall thickness along the deformation zone [81].

However, such significant assumptions and simplifications prevent obtaining a sufficiently accurate result and can be used to identify the averaged characteristics. In more recent studies, the method for determining the law of deformation resistance change is based on solving the original system of differential equations of equilibrium with some additional conditions (plasticity condition, constraint equations, etc.) [18, 82]. Nevertheless, the basic assumptions of the sheet stamping theory were adopted in the solution, which cannot be considered acceptable for describing the process of continuous-incremental upsetting, since it differs significantly by the method of how the thermal energy is delivered into the deformation zone.

Certain studies carried out under the supervision of V. Ya. Osadchy shall be noted—the method for selecting edging passes during pipe upsetting has been analyzed [83]; ways to intensify the process have been outlined and substantiated [84]; methods of its implementation have been proposed [85–87]. The study of V. V. Svetkin analytically and experimentally investigates the conditions for continuous-incremental upsetting of a wide range of pipes (with a diameter from 180 to 273 mm).

The laws of deformation resistance distribution along the plastic deformation zone are proposed, substantiated, and experimentally confirmed [80]. However, the results of the studies correspond satisfactory with the experimental data only for the stationary metal flow, since they do not take into account a number of important factors, such as variations in the upsetting temperature and speed conditions at the initial process stage. While it is the initial stage that is the base for all subsequent deviations to the uniform flow of the operation, but, despite the imperfection and ambiguity of the results, the study [80] can be considered as the first serious step in mathematical modeling of the continuous-incremental upsetting of VCSP.

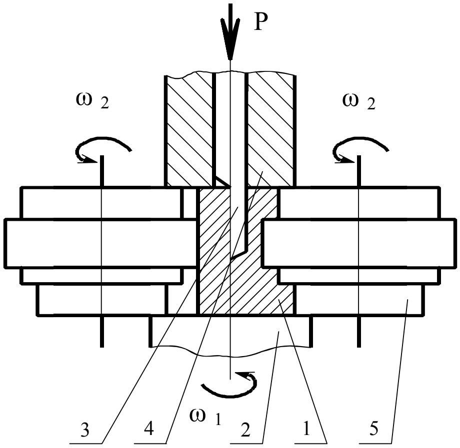

Fig. 1.2 Roll stamping process diagram: *1*–workpiece; *2*–stop; *3*–punch; *4*–puller; *5*–rollers; ω_1—workpiece angular velocity; ω_2—roller angular velocity

Later, multiple works were published [87, 88], in which the initial (unsteady) stage of upsetting was analyzed using variational methods of mathematical analysis [1, 89]. However, despite this approach is modern and involves a strong mathematical apparatus, a number of forced assumptions prevent obtaining an unambiguous conclusion about the mechanism of formation and growth of radial buckles on the resulting barrel, which in practice are the main factor of product rejection.

One of the modern and efficient methods of metal forming for obtaining parts with stepped outer and inner surfaces is roll stamping. This is a pressure forming operation producing axisymmetric parts from cylindrical workpieces by simultaneous application of axial and radial pressure. Axial pressure acting on workpieces during roll stamping is created by a traveling punch, while radial pressure is created by burnishing the lateral surface of the workpiece with rollers or rolls. To summarize, roll stamping [90] is a method of complex local deformation, in which one of the main forging operations is combined into a single production process—piercing or heading (upsetting) with transverse rolling or reeling (Figs. 1.2, and 1.3).

This deformation method allows producing circular cross-sectional solid or hollow parts, thin and thick-walled small-sized products used in instrument making, as well as large parts with high precision and quality using forces with an order of magnitude less than in conventional bulk heading methods.

Complex loading of the plastic deformation zone by local periodic action with simultaneous action via a permanently fixed zone allows obtaining an improved technological effect, not attainable by other deformation methods.

Roller forming improves the physical and mechanical properties of the processed metal and ensures the required fiber pattern, increasing the properties of the resulting parts.

Relatively low cost of tooling, short production equipment preparation time, quick changeover to other part sizes, and use of low-power equipment enable roll stamping to be used both in large-, medium-, and small-scale production.

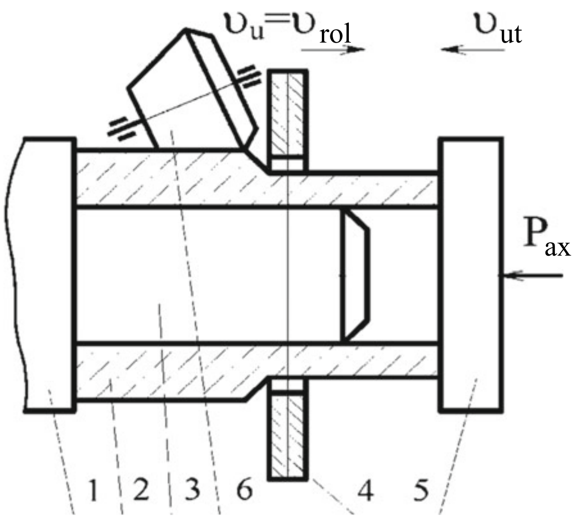

Fig. 1.3 Diagram of continuous-incremental upsetting with a barrel burnished along the outer diameter: *1*–stop; *2*–workpiece; *3*–insert; *4*–inductor; *5*–upsetting tool; *6*–roller; v_i—inductor table velocity; v_{rol}—roller cage feed velocity; v_{ut}—upsetting tool velocity; P_{ax}—upsetting force

As it is possible to limit workpiece forming to the internal cavity's extrusion position and simultaneously perform rolling, and subsequent upsetting, the magnitude of plastic deformation and displaced metal volumes at subsequent processing positions are small, just as are the required deformation forces. This allows refining the part to the required shape and accuracy in subsequent operations.

1.2 Classification of Roll Stamping Processes

Roll stamping processes can be classified according to the following criteria:

- the geometric shape of the original workpiece and the resulting parts;
- the way the workpiece rotation is driven;
- the number of rollers or rolls.

By the geometric shape of the original workpiece and the resulting parts, the parts produced by roll stamping are characterized by the symmetry of all transverse dimensions relative to the workpiece axis. According to the proposed method (Fig. 1.4), two large groups can be derived from the class of axisymmetric parts obtained by roll stamping, differing from each other by the presence of an axial hole.

The first group includes easy-to-manufacture parts without a hole with one or more external bulges located in different parts of the workpiece (plugs, endcaps, etc.). The second group includes parts with a hole, either a blind (with a cavity) or a through hole. The geometry of the outer surface of parts of this group coincides with the shape of the surface of parts without a hole. These are stepped parts with one or more external bulges (flanges, bushings, etc.) and parts without external bulges (sleeves, cups).

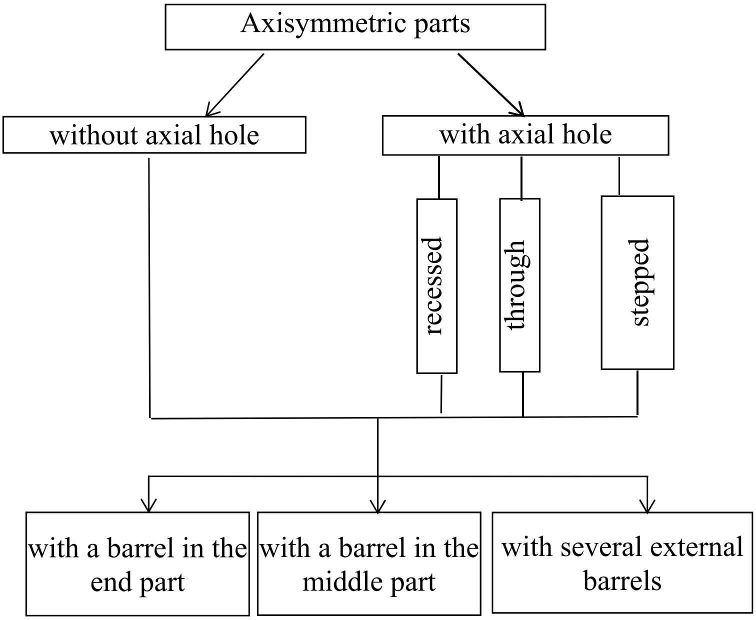

Fig. 1.4 Classification of roll stamping processes by the geometric shape of the resulting parts

Compared to other known methods of bulk heading, the production of axisymmetric parts with a through axial hole by roll stamping is possible due to the specifics of material plastic flow under the conditions of complex local deformation.

By the way, the workpiece rotation is driven. The roll stamping process can be accomplished following one of two kinematic schemes, differing from each other in the way the workpiece rotation is driven. In the first case, workpiece rotation is driven by transferring torque from the driven rolls [91], while in the second case, the torque is transferred to the workpiece from the stop and the punch [92], and the rolls, or in this case, the rollers, are idle.

The roll-driven scheme has a number of disadvantages, one of which is that the frictional moment at large radial reduction may be insufficient to overcome the deformation resistance leading to jamming of the workpiece and driven rolls.

Roll stamping done according to this scheme is more complicated than roll stamping with a rotation drive from a stop and punch, which from the point of view of parts quality improvement, energy cost reduction, productivity, and technological effectiveness of the equipment is more preferable, since it ensures tangential compressive stresses in the local zone, excludes cranking of rollers relative to the workpiece, increases the deformation rate, and allows to apply lubrication to the roller contact surface.

An alternative to such a kinematic scheme is the case when the workpiece side surface deformed by rotating the roller die around it and not the stop and punch. At the same time, it is obvious that the abovementioned scheme does not provide additional advantages but only complicates the design of the production equipment, in particular, makes it practically impossible to control in and out movement of rollers during processing; however, this drive method seems to be the only possibility for the production of large-sized parts.

By the number of rollers or rolls, roll stamping can be accomplished by two-, three-, and multi-roller (or multi-roll) schemes.

In this case, roll rotation drive shall be turned on only after the appearance of forces on the surface of the punch and workpiece, which are sufficient to hold the workpiece in the processing position. Otherwise, the workpiece can be pushed out of the roller die at the first moments of forming (see Fig. 1.5, *b*). Roll stamping in a double-roller die using the scheme with a rotation driven from a stop and punch does not require gripping and positioning devices.

The three-roller scheme is optimal in terms of improving workpiece stability, positioning the workpiece relative to the axis of rotation, and retaining it in a roll die. Furthermore, the maximum roller radius is limited by the size of the original workpiece and is determined by the formula

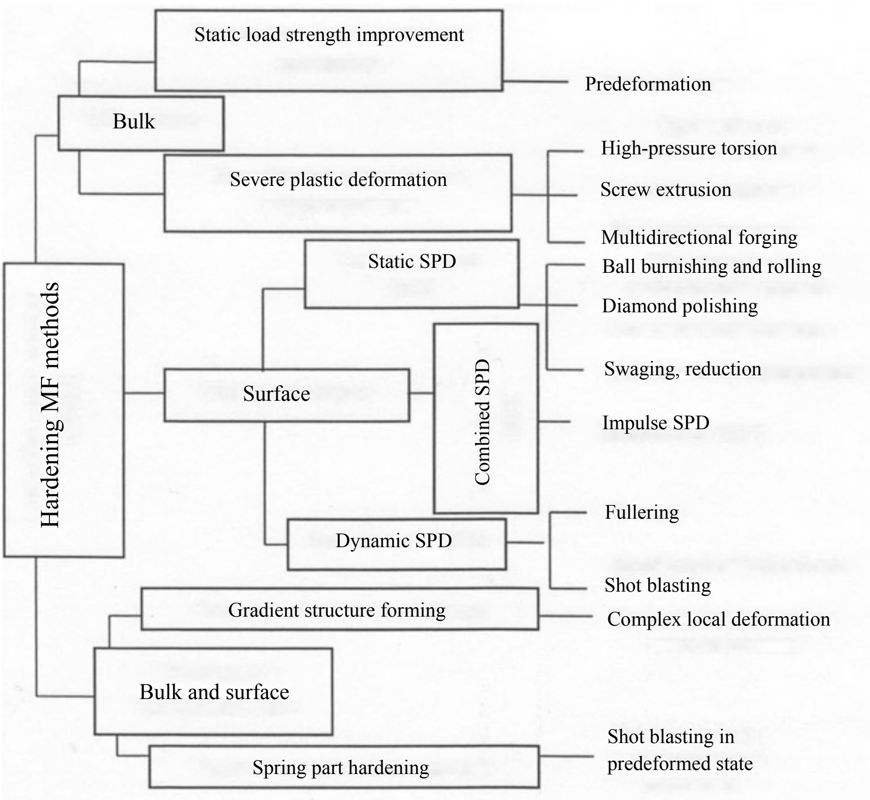

Fig. 1.5 Classification of hardening MF methods

$$R_k^{\max} < 6.4641R, \tag{1.2}$$

where

R is the workpiece radius in mm;
$R_k^{\max}$ is the maximum radius of the roller for a given workpiece radius in mm.

Further increase in the number of rollers decreases their maximum radius, while the workpiece processing depth in the radial direction and the load taken by each of the rollers change as well. The workpiece stability improves, while the process of positioning and retrieving it from the processing position becomes more complicated. Thus, the most feasible is a three-roller die scheme. All theoretical calculations and experimental research in the remaining part of this paper will be related only to this scheme.

The following technological parameters and processing modes have a particularly significant impact on the roll stamping process—ratios of the punch and workpiece radii (R_p/R), as well as the workpiece and roller radii (R/R_k), punch end surface shape, the relative workpiece deformation rate, and the number of rollers and rolls. The relative deformation rate during roll stamping is defined by the ratio of the punch travel velocity to the workpiece rotation frequency. The relative deformation rate determines the amount of the workpiece radial reduction, as well as the process efficiency. The main task of the roll stamping process design is identifying the appropriate technological parameters and processing modes taking into account the specifics of the stress–strain state and plastic flow of metal during the deformation process.

1.3 Hardening by Metal Forming Methods

The increasing requirements of mechanic engineering and instrument making industries in terms of quality, metal consumption, and properties of parts lead to the emergence of new MF hardening methods. The main advantage of MF over other methods of metal forming and structure formation is that plastic deformation under certain temperatures and deformation rates ensures significant work hardening, which is the ground for pressure hardening. Different hardening mechanisms are known for MF—precipitation of dispersed particles, grain refinement, etc. Methods of hardening by MF can be classified by the degree of deformed volume localization (Fig. 1.5):

- bulk hardening—mechanical properties and average grain size are homogeneous throughout the volume, and the product is structurally homogeneous;
- surface hardening with surface plastic deformation (SPD)—the best mechanical properties and the minimum grain size are achieved in the surface layers of the product, and the product is significantly heterogeneous structurally;

- combined bulk and surface plastic hardening—the best mechanical properties and minimum grain size are achieved in the surface and near-surface layers of the product, and the product is structurally heterogeneous.

All shaping processes of MF have bulk hardening effects. Bulk hardening by pressure is used as an independent method to increase the static strength of products—springs, shock absorbers, threaded parts, shafts, and axles. Bulk hardening improves the elastic properties of metal by pretwisting bar stock before producing the final parts or twisting finished parts after heat treatment. Also, this method is used to increase the static strength of parts, and bulk work hardening can be more effective than alloying and heat treatment, since the sensitivity to stress concentration does not increase [93].

For example, oriented bulk work hardening by torsion with stress significantly exceeding the yield point substantially enhances the elastic properties of bainitic or martensitic steel. Bulk plastic deformation applied to hardened steel creates additional opportunities for increasing the strength properties above the maximum level, achievable for steel of this grade by heat treatment. Bulk deformation is also applied at the elastic limit level and is called predeformation. This method is widely used to reduce creep flow, for example, in springs [93].

Severe plastic deformation (SPD) methods should also be considered as bulk hardening methods. The common goal of such processes is the creation of nano- and submicrocrystalline structures in the shaped specimens. The following SPD methods are known—high-pressure torsion, pressure torsion in a composite container, multidirectional forging, fullering, repetitive corrugation and straightening, forced corrugation by pressing, accumulative roll bonding, equal-channel angular or multi-angle extrusion, screw extrusion, widening extrusion, and batch hydrostatic extrusion [94–96].

Currently, the most widespread are two technologies for producing workpieces with nanostructured material states—equal-channel angular extrusion [94] and high-pressure torsion [97].

High-pressure torsion is an advancement of the Bridgman anvil idea. In the first experiments, high-pressure torsion was used to study changes in the recrystallization structure and temperature after significant deformations, as well as to study crystalline transformations. A cylindrical workpiece was placed vertically between flat strikers and restrained. Then rotation was started for one of the strikers, and the specimen was deformed by shear due to contact friction forces. Consequently, the bulk of the material was deformed in quasi-hydrostatic compression—by the force applied to the strikers at the workpiece ends and by the pressure of the outer layers during torsion on the lateral surface. As a result, the deformed specimen did not disrupt despite the significant degree of deformation [96].

Another method that uses deformation of massive specimens by simple shear was developed by V. M. Segal in the 70s of the XX century. This method called "equal-channel angular extrusion" (ECAE) provides the possibility of repeated plastic deformation of materials without changing the product's cross section. In the 90s, R. Z. Valiev and others developed and applied this method for the first time as an SPD

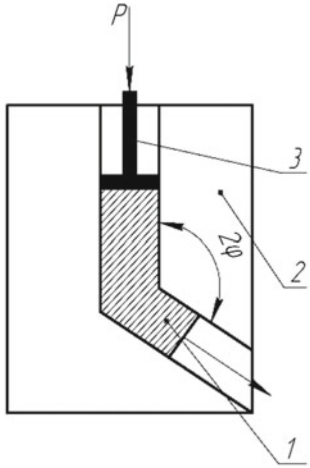

Fig. 1.6 ECAE scheme: *1*–workpiece; *2*–die; *3*–punch

method to obtain structures with submicro- and nanocrystalline grain sizes. Experiments were held with workpieces having round or square cross sections. This resulted in the production of cylindrical metal workpieces with a diameter of up to 60 mm and a length of up to 100 mm with a macrostructure being heterogeneous throughout the volume and grain sizes up to 300–100 nm.

During ECAE (Fig. 1.6), workpiece *1* is repeatedly pressed by a punch *3* in a special tooling *2* via two channels with the same cross sections intersecting at an angle of 2φ (usually 90°). Deformation is performed at higher temperatures in the case of hard-to-deform materials.

The number of workpiece passes through the channels is important for structure formation during the ECAE process. Pressing routes have a crucial role as well (orientation of the workpiece relative to its axis during passes). Different routes are used during experimental studies. After each pass, the workpiece is rotated around its longitudinal axis by 90 or 180°. These routes differ in the shear direction during repeated passes of the workpiece through intersecting channels, which leads to a different shape change of the spherical cell in the workpiece body [94].

The screw extrusion process proposed in 1999 Ya. Ye. Beigelsiemer shall be noted as well. In this method, the prismatic workpiece is pushed through a die having a screw-shaped channel. The angle of the screw line inclination to the extrusion axis changes along the die height and is equal to zero in its initial and final sections.

Die channel geometry completely preserves the shape and dimensions of the workpiece, allowing its repeated extrusion in order to accumulate large degrees of deformation [95]. SPD methods allow obtaining products with a unique set of properties. The material subjected to severe deformation has homogeneous mechanical properties and an optimal ratio of strength and ductility.

However, SPD methods require powerful equipment and expensive tooling; therefore, the range of products obtained by these methods is significantly limited. Furthermore, these methods cannot be used for processing already obtained products of complex shapes, for example, stepped shafts or beams.

Hardening by surface plastic deformation (SPD)—SPD is one of the most effective ways to improve the properties of machine parts [93, 98–102]. Hardening is performed to increase the fatigue resistance and hardness of the metal's surface layer, as well as to form directed internal stresses (mainly compression stresses) and the required surface microroughness. Various SPD methods are widely used—burnishing with rollers or balls, diamond polishing, hole mandrelling, shot blasting, hydroblasting and pneumatic hydroblasting, vibration-assisted attrition treatment, fullering, ultrasonic treatment, etc.

By hardening effect, SPD methods are divided into static and shock (dynamic). Static SPD methods (polishing, burnishing, etc.) act on the deformation zone with a constant flow of energy and continuous contact between the tool and the part. Dynamic SPD methods (shot blasting, hydroblasting, and pneumatic hydroblasting, etc.) imply using an impact deformation on the treated surface of working bodies or tools having intermittent contact.

Surface work hardening is often used in finishing operations of the machine part production instead of finishing operations by cutting with razor or abrasive tools.

Static SWH methods—Rolling or roll burnishing with balls (Fig. 1.7) and rollers (Fig. 1.8) is mainly performed using lathes.

The tool (roll burnisher) is fixed in the tool holder and the workpiece—in the mandrels and/or in the chuck. The rolling pressure can be generated by a calibrated spring or by pneumatic or hydraulic mechanism.

One of the most common static SPD methods is surface burnishing with rollers of various designs [101, 103]. This method has high performance and is simple, affordable, and cost effective.

When treating surfaces of complex geometry, rollers are used that repeat the shape of the treated surface (Fig. 1.9).

Workpiece *1* (cast and machined on the outer and inner surfaces) is fixed on rotating mandrels, *2*. stepped rollers *3* are pressed against the rim surface with a force

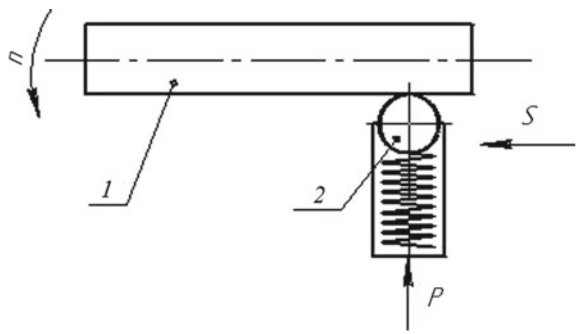

Fig. 1.7 Burnishing with an elastic single-ball roll burnisher: *1*–workpiece; *2*–roll burnisher

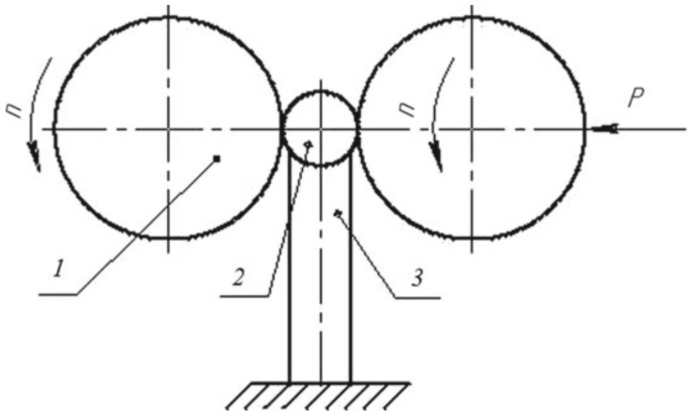

Fig. 1.8 Rolling with rolls: *1*–rolls; *2*–workpiece; *3*–stop

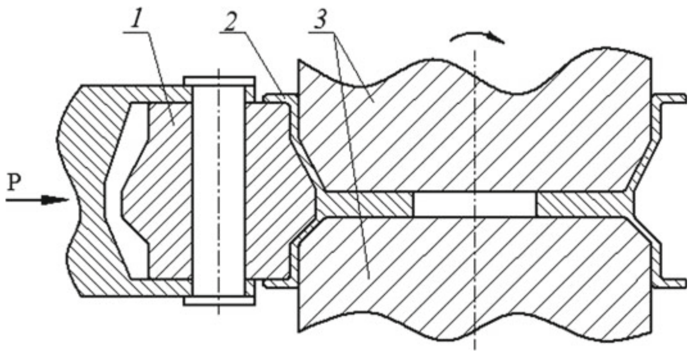

Fig. 1.9 Burnishing a thin-walled workpiece with rollers: *1*–workpiece; *2*–insert; *3*–roller

P, and burnishing operation is commenced [104]. This method allows hardening the workpiece surface to reduce its roughness, which has a positive effect on the final product properties.

Burnishing efficiency using rollers to a large extent depends on the correct choice of the treatment method, burnishing mode, as well as power and geometric parameters of the process. However, it should be noted that the shown method is often used not for hardening, but for improving the geometry of the product and its surface quality. In fact, during such a roll burnishing process, a backward creep zone is formed after the roller contact patch with tangential tensile stresses appearing on the workpiece surface, which prevents the accumulation of deformations necessary for significant hardening without destroying (peeling) the product's surface layer.

Diamond polishing (Fig. 1.10) implies a plastic deformation by a tool (burnisher) sliding along the treated surface [103].

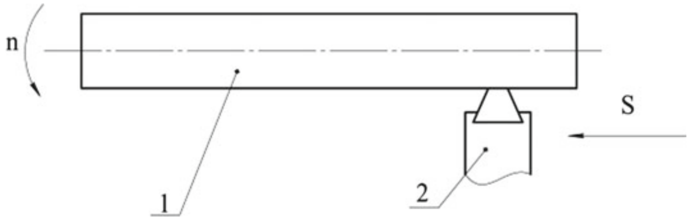

Fig. 1.10 Polishing with an indentor with diamond tip: *1*–treated workpiece; *2*–diamond burnisher

The tool forms a groove along a helical line on the workpiece surface, while the small radius of the indenter's deforming surface produces small polishing forces, which allows treating thin-walled and non-rigid parts. Due to the high hardness of diamond, it can be used to treat almost all structural metals and alloys, while a greater positive effect of diamond tip burnishing affects steels with high surface hardness, including hardened and case-hardened steels [103, 104].

Mandrelling (reduction) is divided into surface and bulk [99, 105]. At surface mandrelling, the surface layer is plastically deformed, at bulk mandrelling—plastic flow occurs over the entire workpiece cross section, which actually makes it a bulk deformation; however, it is more practical to consider these processes together due to tooling similarity.

Mandrelling of hollow cylinders is carried out with a simple tool (mandrel, die) on a multi-purpose broaching and pressing equipment. Mandrelling of bushing and sleeve holes with large interference is performed by deforming broaches, piercings with a diameter larger than the workpiece hole by the interference value. This process is known as deforming broaching or free mandrelling. Free reduction of cylindrical surfaces of fingers and plungers is performed by pushing, pulling (drawing) through dies (drawing dies), blocks of dies having the hole diameter lesser than the outer workpiece diameter by the full interference value.

This process is described in the reference sources as reduction, compression, and pipe drawing. For simultaneous precise processing of cylinder surfaces (notably, one surface can be shaped), the reduction is carried out by limiting the radial and axial metal flow by a special mandrel (case).

Dynamic SPD methods—shot blasting (Fig. 1.11) implies workpiece surface treatment with a stream of dry shots or shots in a special liquid (coolant) [106, 107].

Shots (steel, cast iron, or glass) propelled by a jet of compressed air, coolant, or reflected from the blades of a rapidly rotating rotor, under the action of inertial forces from their mass, produced multiple point surface hardening of the part.

Shot blasting machines are widely used due to their high productivity, versatility, and efficiency in local treating of large parts [106, 108]. Similar equipment is used to remove process thickeners and harden the welded areas. Though shot processing has significant drawbacks—high surface roughness after processing, irregular microscale topography, process instability, impossibility of deformation of thin-walled parts, and lack of scientifically based methods for determining the most efficient process

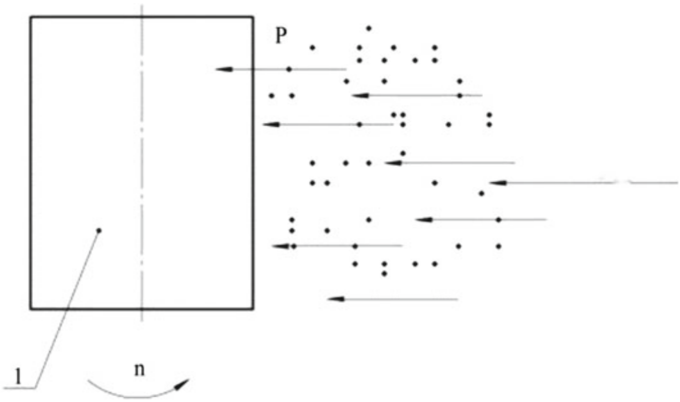

Fig. 1.11 Shot blasting: *1*–treated workpiece

parameters. Therefore, shot blasting is used for parts that do not have too high requirements to the surface quality.

The processes of vibration-assisted roller burnishing and vibration-assisted polishing are known (Fig. 1.12), which have reciprocating movement imparted along the axis of the rotating workpiece in addition to the axial travel of the tool pressed against the workpiece.

The movement of the deforming element along the axis is dynamic in nature and has the appropriate frequency and amplitude. If a hardened steel ball is used as a tool, then the process is called vibration-assisted roller burnishing and if a spherical tip is made of diamond or other superhard material—vibration-assisted polishing, since the process is based on sliding friction.

Fullering provides the greatest depth of the hardened layer among all SPD methods—up to 30–40 mm [101]. Depressions of splines, large threads, and other stress concentrators are subjected to fullering. The main disadvantage of fullering is the increased roughness of the machined surface; therefore, the surface is usually ground after fullering.

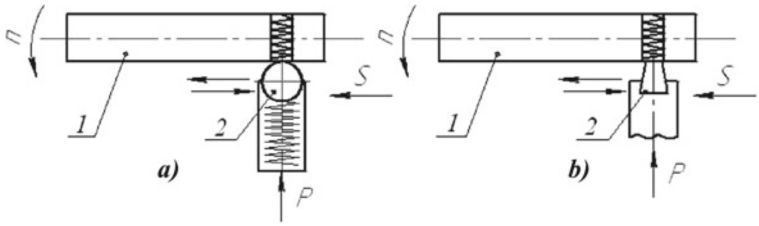

Fig. 1.12 Vibration-assisted burnishing: **a** vibration-assisted roller burnishing; **b** vibration-assisted polishing; *1*–workpiece; *2*–tool (hardened ball, diamond burnisher)

SPD methods also include ultrasonic hardening [101, 109]. It provides extremely low surface roughness, high contact rigidity, and wear resistance, as well as 40% greater fatigue resistance than polished parts. Due to the complexity of the equipment, the high cost of ultrasonic generators, high energy consumption, and the need for large production areas, ultrasonic hardening has not found widespread application.

During centrifugal treatment of parts, the treated surface is successively impacted by working elements (balls or rollers) freely located in the radial holes of the rotating disk [101, 110]. This method is used to increase the fatigue resistance of parts operating under severe operating conditions. With correctly selected hardening modes, this method can increase the fatigue resistance of machined parts by 1.5–4 times. The disadvantages of this hardening method include high tooling cost and the need for precise placement of the balls in the separator, which also requires careful balancing.

Wire tools are also used for hardening: wire brush, disk, and butt brushes, which sometimes include impact elements [99, 101, 111].

Brushing involves complex physical, mechanical, and chemical processes occurring in the treated surface—wire sliding along the surface, destruction of oxide films, micro-impacts of individual wires, microcutting, etc. The disadvantages of brushing include possible part surface damage, high tooling cost, the need to experimentally determine the optimal processing parameters in each specific case.

Dynamic SPD methods can achieve a greater degree of surface hardening than static methods, though at a cost of a lower surface quality. The disadvantage of all dynamic methods is that they are poorly studied, which leads to a lack of generalizing results and conclusions.

Combined SPD methods combining static and dynamic loading during treatment are quite widespread in practice. Hardening with a combined (static and dynamic) load creates additional opportunities for surface formation, and the hardening technology includes preliminary static and subsequent dynamic loading of the tool [99].

During a combined SPD hardening process, deforming tool *1* is pressed against the machined surface of part *4* with the force P_{i} generated by spring *5*, which provides static loading P_{st} (Fig. 1.13) [99].

On the other side, instrument *1* is connected via concentrator *2* to ultrasonic generator *3*, which provides impulse load, while the impulse load amplitude is up to three times higher than the static load.

Other combined treatment methods are also used; however, the common disadvantages of such treatment are low efficiency, low productivity, and difficulty to control the process.

Parts hardened by various SPD methods have different roughness, different values of residual stresses, and their depth (Fig. 1.14) [93, 99, 101, 102].

Therefore, the selection of a specific SPD method shall be guided not only by the technological and economic feasibility, but also shall take into account the conditions of subsequent product treatment and operation.

The disadvantages of SPD methods are obvious—a small depth of work hardening, presence of a transition boundary (sometimes a sharp on) from the hardened layer to the deeper unmodified layers, and high probability of excessive amount of work

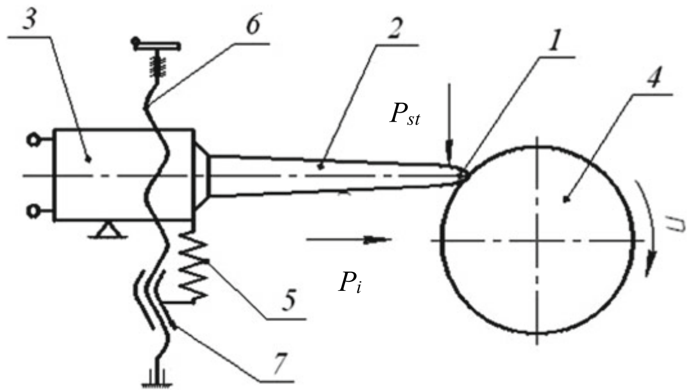

Fig. 1.13 Loading diagram for hardening with a combined (static and dynamic) loads: *1*–deforming tool; *2*–concentrator; *3*–ultrasonic generator; *4*–workpiece; *5*–spring; *6*–lead screw; *7*–nut

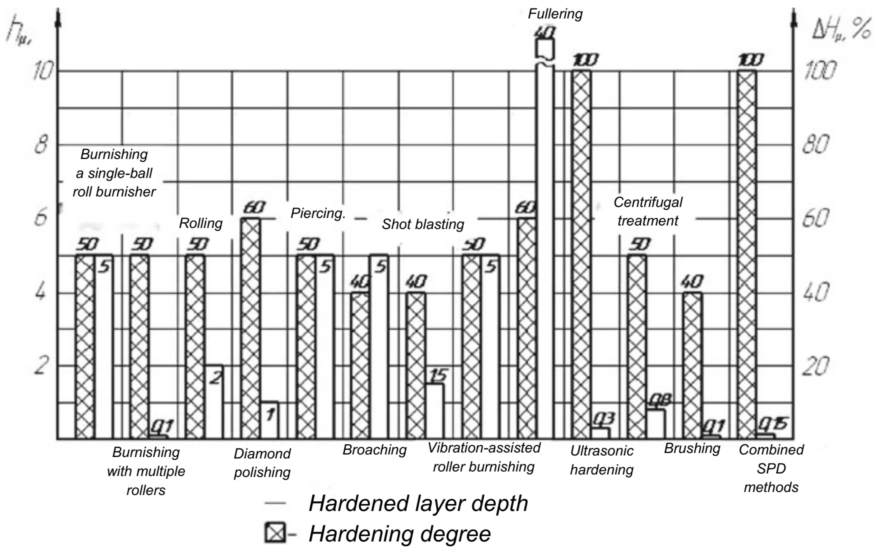

Fig. 1.14 Description of methods of hardening by surface plastic deformation

hardening. These disadvantages come from a small spherical strain tensor, since the treatment is carried out according to schemes that are far from the multi-directional compression scheme.

Methods that combine bulk and surface plastic deformation can be divided into technologies for treating spring parts and technologies for creating gradient structures.

The first group includes hardening that combines bulk-oriented deformation with surface work hardening (stress work hardening). This technology is one of the most effective methods to increase fatigue strength [93]. For example, the endurance limit of wire springs with this type of treatment increases twofold. Such hardening conditions are also created when flat shock absorbers are hardened with shot blasting in a predeformed state.

Bulk deformation stresses shall not exceed the elastic limit values. Bulk deformation with stresses not exceeding the yield point is directed in a way to stretch the treated surface. Certainly, elastic bending is performed in the same direction the shock absorber will deform during operation. This hardening method increases shock absorber durability up to 20-fold, as well as increases the residual compressive stresses by 30% in comparison with conventional shot blast hardening, while the elastic properties remain at the pretreatment level [93, 112].

Another method that combines surface and bulk plastic deformation is complex local deformation [90, 104, 113–116], which allows forming gradient submicro- and nanostructures in a product [117–119]. The method combines global loading affecting the entire volume of the workpiece, and local, which intensely deforms only a separate section, in a single technological process, while one of the loads (more often local) has an unsteady state.

One of these methods is roll stamping (RS) (Fig. 1.15) based on combining bulk cold stamping operations (heading, piercing) and local deformation by transverse rolling or burnishing in a single production process [90, 114]. Punch or upsetting tool *2* continuously impacts the deformable section of workpiece *2*, while rolls (rollers) *1* create local discrete loading periodically alternated with unloading.

RS is successfully used to obtain solid and hollow parts and super thin-walled and thick-walled products. RS method allows obtaining small parts used in instrument making and large parts for the machine engineering or aviation industry. Products have high precision and production quality at forces during production that are an order of magnitude lower than for conventional methods of bulk cold stamping [120].

A logical further advancement of the RS method was the development of a number of new technologies and devices [96, 113, 116, 117, 119, 121–124]. These technologies allow to achieve significant surface hardening, distribute mechanical parameters along a certain gradient deep into the workpiece, as well as to form submicro- and nanocrystalline structure gradients in final products.

Fig. 1.15 Roll stamping scheme: *1*–rolls (rollers); *2*–punch; *3*–workpiece; *4*–stop