Journal of the Technical University of Gabrovo

https://mc04.manuscriptcentral.com/jtug

METHODS FOR INCREASING THE FATIGUE LIFE OF STRUCTURAL COMPONENTS WITH FASTENER HOLES - STATE OF THE ART

Galya Duncheva*, Petya Daskalova
Technical University of Gabrovo, 5300 Gabrovo, Bulgaria

ARTICLE INFO

Article history:
Received 23 May 2024
Accepted 28 June 2024

Keywords:
fatigue life, fastener holes, cold working, surface integrity, compressive hoop residual stresses

http://doi.org/10.62853/JNWG1335

ABSTRACT

The article reviews the main approaches and the methods that implement them to improve the fatigue behavior of metal structural elements with fastener holes. A generalized classification scheme is proposed, in which established methods in engineering practice and new methods are systematized. The generalized scheme was developed based on the differential-morphological method. In accordance with the differentiation of the methods in the generalized scheme, the principle schemes of the different groups are visualized and an analysis of their advantages and disadvantages was made from the point of view of their functional capabilities and in a technological aspect.

1. INTRODUCTION

Holes are among the most common natural stress and strain concentrators in metal structural elements. In general and precision engineering, as well as in transport technology, dynamic and, in particular, cyclic loads dominate, which is why the strength resource of structural elements is limited by fatigue damage caused by the initiation and development of fatigue cracks in the areas around the openings.

Fatigue failures typically occur in the aerospace, rail, automotive, and marine industries. In these sectors, the competitive market imposes requirements for operation at ever greater loads and speeds, which is why the sources of vibrations and dynamic loads in structures are increasing. Under these conditions, prevention against fatigue becomes increasingly important, since, in addition to preventing material losses, the primary task is to protect the human factor.

The first systematic studies of the material fatigue phenomenon are related to the development of railway transport in the 19th century. Rankin (1843) and McConnell (1849) observed the nature of the fracture in locomotive and wagon axles destroyed as a result of prolonged cyclic loading. The prevention of metal fatigue damage in various structural parts in aircraft construction has been a subject of great interest since the first half of the 20th century. In 1941, the US Bureau of Aeronautics sponsored the preparation of a book on the prevention of repetitive stress damage to metals prepared by the Battelle Memorial Institute. According to statistics, the relative share of fatigue failures in aircraft in service is 50-90 % of all component failures (Liu et al, 2007; Liu et al, 2010; Abdelkrim et al., 2014). Fatigue cracks usually initiate near the numerous bolt or rivet holes located in the fuselage, wing skins, access panels, etc. Therefore, the fatigue life, load-bearing capacity and operational safety of the components are limited by the complex state of the material around the holes. Hence, approaches to fatigue failure prevention of components with fastener holes are aimed at modifying the material around the holes.

A pioneering method for improving fatigue behavior developed specifically for applications in the aerospace industry was patented by Boeing (Champoux, 1971) and was based on the concept of cold hole expansion. Its essence lies in the preliminary creation of a deep zone of beneficial hoop compressive residual stresses (RSs) around the fastener holes. This zone reduces the effect of stress concentration around the holes and repeatedly slows down the formation and growth of dangerous firsttype fatigue cracks - tear cracks. Over the years, anumber of methods have been developed and improved, focusing on the distribution of hoopRSs and the beneficial effect of the compressive zone (Champoux, 1984; Champoux, 1985; Hogenhout, 1986; Quincey et al., 1994; Easterbrook, 2001; Chakherlou and Vogwell, 2004; Maksimov and Duncheva, 2014).

A general approach for introducing compressive RSs into metal structural elements is the mechanical cold working process, which is realized at a temperature lower than the recrystallization temperature of the corresponding metal. When this approach is carried out in the surface cold working variant, the aim is to modify the complex state of the surface and subsurface layers, known as Surface integrity (SI). Regarding components with holes, static

* Corresponding author. E-mail: duncheva@tugab.bg

surface cold working methods, known as burnishing, are more popular. Known applications are mainly related to deep rolling (Nguyen and Le, 2019) and diamond burnishing (Duncheva et al, 2022; Maximov et al, 2014; Maximov et al, 2019a). Surface cold working causes smoothing of the asperities (smoothing effect) and strain hardening effect, which are evaluated with interdependent characteristics of SI – 2D and 3D surface texture parameters, microhardness, RSs distribution, and microstructure. Therefore, the compressive RSs introduced around the hole is one of the effects after surface cold working, which is directly dependent on the geometrical and physical-mechanical characteristics of the SI around the hole. In this context, a trend for a wider scope of research on processes based on cold hole expansion has been observed recently.In addition to the RSs distribution, the efficiency of the processes is also evaluated by different characteristics of the surface layers around the holes - surface topography and microstructure (Faghih et al, 2020; Wang et al, 2021; Wang et al, 2023).

Based on the overview of the main approaches for improving the fatigue behavior of metal structural elements with fastener holes, in the present study a generalized classification scheme of the methods for improving the fatigue behavior of metal structural elements with fastening holes is proposed. The object of systematization are the established methods in engineering practice and the new methods for treating holes, as an analysis of their advantages and disadvantages was made.

2. A GENERALIZED CLASSIFICATION SCHEME

The generalized classification scheme was developed on the basis of the differential- morphological method, which is a universal tool for classifying various objects and processes using hierarchically organized relevant signs and sub-signs. The differential-morphological method was developed by Y. N. Kuznetsov (Hamuiela et al, 2017) on the basis of the morphological method proposed by the Swiss astronomer Fritz Zwicky (Bliumberg and Glushtenko, 1982). According to the differential-morphological method, each element is uniquely identified with a corresponding letter or alphanumeric code in accordance with the hierarchical level of the used morphological signs and sub-signs. In the generalized classification scheme (Fig. 1) for main classification signs at the first level, the main approaches for modifying the material around fastener holes are adopted, indicated as follows:

- A – Surface cold working;
- B – Introducing of beneficial compressive hoop RSs;
- C – Introducing of beneficial compressive hoop RSs and improving in SI.

At the next hierarchical levels in the generalized classification scheme, for each of the main approaches, a classification of the methods implementing them is made. For this purpose, their defining characteristics, accepted as sub-characteristics, were selected. The specific methods for increasing the fatigue life of structural elements with holes are shown in the last hierarchical level (Fig. 1).

3. ANALYSIS OF MODERN METHODS FOR INCREASING THE FATIGUE LIFE OF STRUCTURAL ELEMENTS WITH FASTENER HOLES

3.1. Methods, based on Surface Cold Working

Surface cold working is a fundamental approach to modify the complex state of the surface layers (SLs) of metal structural elements. The improvement in SI results from three main effects: 1). Smoothing effect due to local plastic deformation at the peaks of asperities; 2). Strain hardening effect due to cold work; 3). Introducing beneficial compressive residual stresses (RSs) into the surface and subsurface layer.

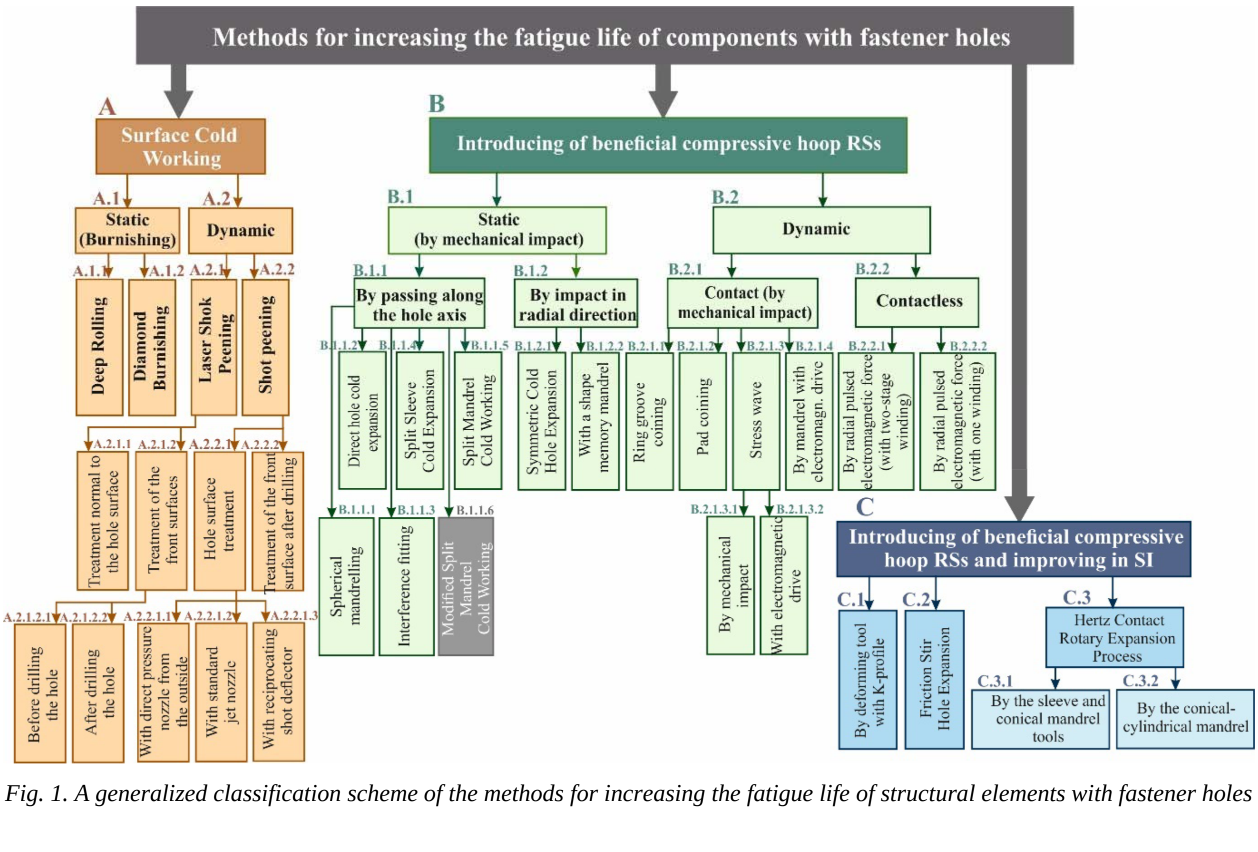

Fig. 1. A generalized classification scheme of the methods for increasing the fatigue life of structural elements with fastener holes

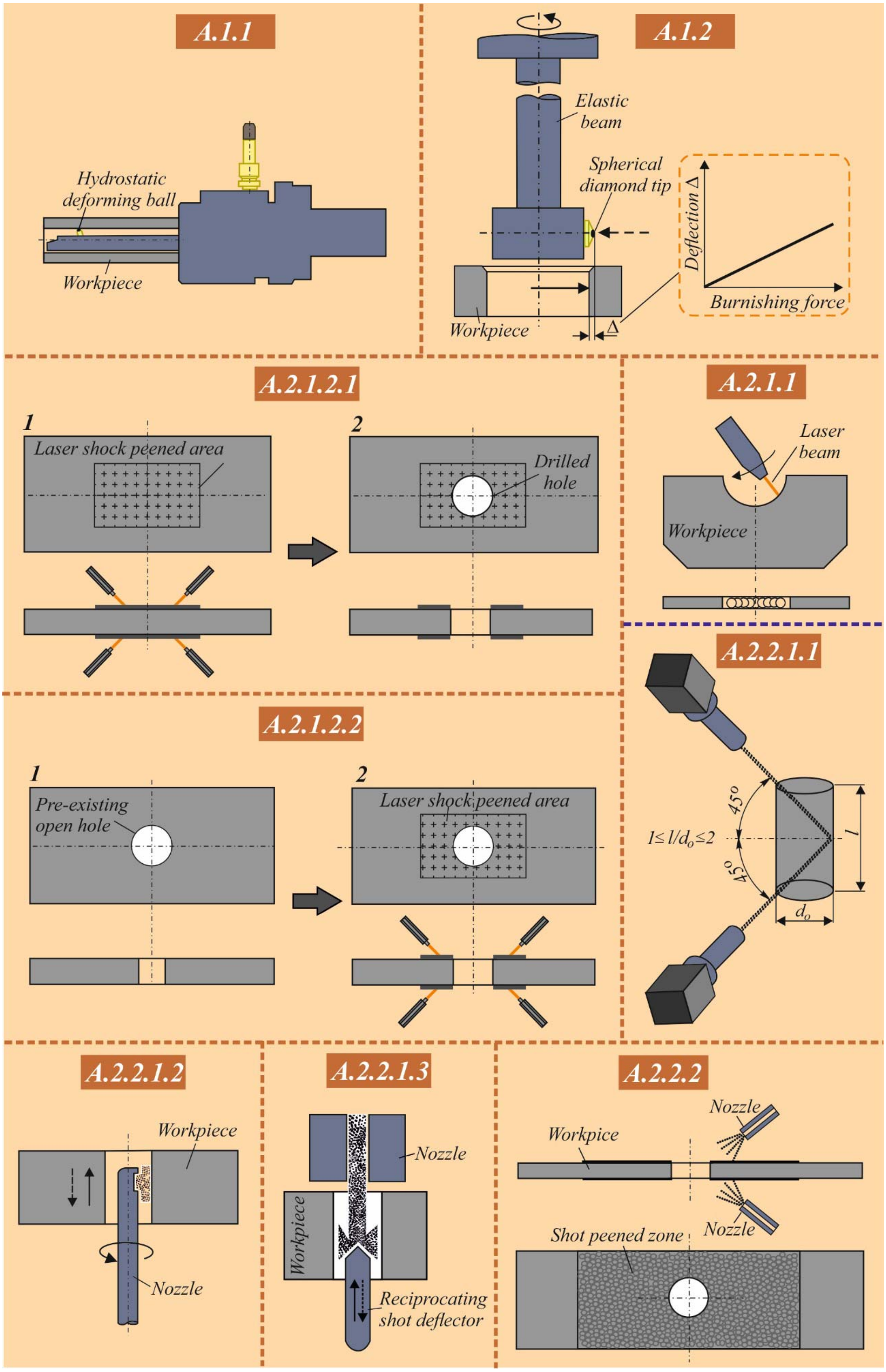

Fig. 2. Principle schemes of the methods based onsurface cold working

An up-to-date classification of methods based on surface cold working is made by Maximov et al., (2019b). According to the way of application of the deforming impact, the methods are static (Fig. 1, groups A.1) and dynamic (Fig. 1, groups A.2). Chronologically, dynamic methods precede static ones. In the case of dynamic methods, the plastic deformation of the surface layer is a consequence of impact or impulse impact, which reflects in the inhomogeneous plastic deformation in the surface and subsurface layers. In static methods, known as burnishing, the deforming element/s is statically pressed against the treated surface. As a result, the process of plastic deformation is continuous in time, and the cold work size and strain rate depend on the technological parameters of the relevant process. The schematic diagrams of the most widely used surface cold working methods for hole finishing are shown in Fig. 2. The designations of the methods correspond to the accepted designations in the generalized classification scheme (Fig. 1).

3.1.1. Static surface cold working methods (burnishing methods) (group A.1)

The use of the roller burnishing method for hole treatment aims above all to achieve a very low roughness (mirror-like surface) and accuracy (Ecoroll – catalog http://teco.net.au/-pdf/-ecoroll/-ecoroll-catalog_en_web .pdf), and the effects of strain hardening and the creation of a zone with useful compressive RSs are less pronounced. However, when the main goal is to improve fatigue behavior, the last two effects are decisive, and the smoothing effect is concomitant. In this aspect, suitable burnishing methods for finishing holes are hydrostatic ball burnishing (Fig. 2, diagram A.1.1) – a typical representative of the deep rolling concept presented by Ecoroll, and diamond burnishing (Fig. 2, diagram A.1.2). These methods differ according to the tangential contact used between the deforming element and the surface of the hole - respectively rolling friction and sliding friction contact. This predetermines different deformation processes, and hence – a different complex of SI characteristics (Maximov et al, 2020).

Hydrostatic ball burnishing (scheme A.1.1) uses a deforming ball subjected to a hydrostatic pressure, which requires a high-pressure station (Ecorollcataloge). There is a wide nomenclature of type HG tools of the Ecoroll company, implementing hydrostatic ball burnishing, but due to design limitations, the conventional options are applicable for treating holes with diameters greater than 19 mm. Despite the fact that special instruments for the treatment of cylindrical holes are presented, there are no studies in the literature related to the effect of their application. Moreover, for finishing cylindrical holes, Raza and Kumar, (2022) present roller burnishing tool (multiple tool) in their critical review, dedicated to tool design in burnishing process.

Of the methods using sliding friction, the diamond burnishing (DB) method has the greatest practical application (scheme A.1.2). The deforming element at DB is a diamond crystal (artificial or natural) with a very high hardness, which allows the processing of the hardest metals and their alloys. Considerably more research has been devoted to the effectiveness of the DB as a finishing process of components with holes in various applications: enhancement of fatigue life of rail-end-bolt holes (Maximov et al, 2014a; Maximov et al, 2017), crack resistance enhancement of joint bar holes (Maximov et al, 2019), enhancement of SI and tribological behavior of sliding bearing bushings made of CuAl8Fe3 bronze (Duncheva et al., 2022a) and CuAl9Fe4 bronze (Duncheva et al., 2022).

A schematic diagram of a device for DB of holes with an elastic beam is shown in Fig. 2 (A.1.2). The burnishing force F_b is set when positioning the device by means of the distance between the tip of the diamond deforming element and the surface of the hole in the radial direction. Physically, this distance corresponds to the deflection Δ when bending the elastic beam of the device, which is determined by the well-known formula:

$$\Delta = \frac{F_b l^3}{3EJ}, \tag{1}$$

where: l is the length of the elastic beam, E is Young's modulus, $J = \frac{\pi d^4}{64}$ is the axial moment of inertia of the cross section of the elastic beam, d is the diameter of the cross section of the beam. The implementation of the DB process using the device according to scheme A.1.2 provides very low roughness, increased microhardness and significant useful residual compressive stresses (Maximov et al, 2019; Duncheva et al., 2022; Duncheva et al., 2022a).

The burnishing methods are particularly suitable for treating rotary surfaces, shafts, axles, and fastener holes. Their advantage is the possibility to manage the technological parameters in correlation with SI obtained, and hence the fatigue behavior.

3.1.2. Dynamic surface cold working methods (group A.2)

Shot peening (SP) is the most popular dynamic method in which the surface is bombarded withalarge number of small steel, glass or ceramic spheres. Regarding components with fastener holes, SP is applied in two variants (Fig. 1): 1). Hole surface treatment (A.2.2.1); 2). Treatment of the front surfaces after drilling (A.2.2.2). The following techniques exist for SP directly on the hole surface (Bozdana, 2005): 1). Quadrant peening; 2). With direct pressure nozzle from the outside (Fig. 2, scheme A.2.2.1.1); 3). With standard jet nozzle (rotary lance peening) (Fig.2, scheme A.2.2.1.2); 4). With reciprocating shot deflector (deflector lance peening) (Fig. 2, scheme A.2.2.1.3). The above four techniques are used to improve the fatigue behavior of components with holes in the aerospace industry – holes in housings, shafts and flanges, holes for pins or ports for cables or fluids. The choice of the appropriate technique depends on the geometry of the holes (the length/diameter ratio l/d_0 , the type of holes (through or blind), access).

The quadrant peening is designed for one-sided access treatment of bolt holes in flanges for which typically $\frac{l}{d_0} < 2$ (Bozdana, 2005). Each nozzle is directed at a 45° angle to a quarter of the hole. As a result of the rotation of the flange, the portion of the bore that is subjected to direct shooting at each nozzle location is moved 90° for each rotation. SP with direct pressure nozzle from the outside (A.2.2.1.1) (Fig. 2) is suitable for relatively longer through holes ($l \le l/d_0 \le 2$). SP with standard jet nozzle is a flexible but slow process that can also be applied to blind holes. As shown in scheme A.2.2.1.2 (Fig. 2) rotating nozzles are actually deflector nozzles that rotate around their axis. SP with reciprocating shot deflector (deflector lance peening) (Fig. 2, A.2.2.1.3) is used to treat deep holes. To ensure adequate coverage, the deflector pin performs a translational movement in the holeaxis direction, and the part with the hole rotates about this axis.

The effectiveness of SP of the front surfaces after drilling on fatigue behavior of open-hole steel plates for 200 % and 400 % coverage compared to as-machined has been proven experimentally (Wang et al, 2020).

Disadvantages of SP is the control of the complete coverage of the treated surface and its characteristic surface morphology, characterized by small pits, respectively the roughness obtained is unacceptable.

Laser Shock Peening (LSP) (A.2.1) (Fig. 1) is an advanced surface cold working technique to improve fatigue properties by introducing residual compressive stresses and modifying the microstructure (Gu et al, 2022; Achintha et al, 2014; Ivetic et al, 2012; Sikhamov et al, 2020). Laser pulses in LSP are focused on the top surface of the respective components so that an ablative layer – usually black paint or a thin metal foil – is vaporized (Bozdana, 2005). As a result, a hot plasma is created, the expansion of which causes shock waves in the treated material. The latter provokes significant plastic deformation in the SLs and subsurface layers. Regarding components with holes, LSP applies in two variants: 1). Treatment normal to the hole surface (Fig. 2, scheme A.2.1.1) (Gu et al, 2022); 2). Treatment of the front surfaces (A.2.1.2). LSP in option A.2.1.2 can be applied before hole drilling (Fig. 2, scheme A.2.1.2.1) or after drilling it (Fig. 2, scheme A.2.1.2.2). Front surface treatment techniques are more effective on relatively thinner sheet components.

Comparison of the effectiveness of techniques A.2.1.2.1 and A.2.1.2.2 on fatigue behavior is the subject of experimental and numerical studies. For thin aluminum specimens (3 mm thick), Ivetic et al, (2012) found that when the hole was drilled after LSP treatment, the distribution of RSs across the thickness of the specimens was entirely compressive. This result supports the experimental results of greater fatigue life. Sikhamov et al, (2020) investigated both techniques with and without an initial crack in AA2024-T3 specimens. They found that post-LSP treatment significantly extended the fatigue life of specimens with an initial fatigue crack, and as expected, this effect was greater the shorter the crack length.

3.2. Methods for introducing beneficial hoop compressive RSs

3.2.1. Static methods (group B.1)

In static methods, the introduction of beneficialhoop compressive RSs around the holes is a consequence of mechanical impact on the surface of the previously processed hole, causing plastic deformation at a relatively large depth. The main characteristic of the methods of group B.1 is the low strain rate: from 1×10^{-4} to 1×10^{-3}, s^{-1}, which predetermines a slight increase in temperature (Duncheva, 2017). According to the way in which the mechanical impact is applied to the surface of the previously processed hole, the static methods are differentiated into the following subgroups (Fig. 1): 1). By passing along the hole axis (B.1.1); 2). By impact in radial direction (B.1.2). The schematic diagrams of the most common static methods are visualized in Fig. 3, and their designations correspond to those of Fig. 1.

In most methods of subgroup B.1.1, cold expansion is a result of rectilinear translation of the tool (deforming mandrel) along the axis of the previously machined hole. An exception is the Spherical mandrelling method (Fig. 3, scheme B.1.1.1), which is distinguished by specific kinematics. With respect to the fixed detail, the tool performs a complex movement - spherical movement (adding rotations around intersecting axes) and translation along the hole axis. The tool rotates around its own axis with an angular velocity ω_r and at the same time rotates around the axis of the hole with an angular velocity ω_e. The two axes intersect at a small angle of nutation θ (Maximov and Duncheva, 2008). All other things being equal, the described kinematics reflects in a significantly smaller axial force compared to the conventional case of pure translation. This enables the Spherical mandrelling process to be implemented on conventional and CNC milling machines using special devices.

In subgroup B.1.1 methods based on a translationally through-hole mandrel, the plate is expanded layer by layer from the entrance side to the exit side. This process is characterized by a plastic deformation wave moving in the direction of the hole axis along with the moving mandrel. As a result, the stress tensor for points near the hole surface contains tangential components (Duncheva, 2017). As a consequence of the differences in the boundary conditions, the hole surface is subjected to uneven expansion along the hole axis. Therefore, the process of deformation in the methods of subgroup process B.1.1 is three-dimensional, which leads to a non-uniform stressed and strained state in the different cross-sections along the thickness of the plate. On the entrance side, the stressed state is two-dimensional and the strained state is three-dimensional.The points of the middle section of the plate arein a stateclose to plane strain state. In the points from the exit side contacting with the support, the stressed state is three-dimensional. This inhomogeneous stressed and strained state results in a significant axial gradient in the distribution of RSs (Maximov and Duncheva, 2008; Garcia-Granada et al, 2000; Stuart et al, 2011; Yuan et al, 2015). One approach to homogenize the field of RSs in the axial direction is to remove a layer of metal around cold-expanded holes by secondary reaming (Maximov et al, 2012). The effect is due to the redistribution of RSs due to the potential energy of deformation around the hole accumulated during cold expansion. At the same time, the undesirable effect (the so-called "surface upset" around the hole edges which is more pronounced on the exit face) due to axial deformations is greatly reduced.

Direct cold expansion (Fig. 3, scheme B.1.1.2) consists in passing of a mandrel from end to end through the hole, the working part of which has a diameter d_t greater than the diameter d_0 of the previously made hole. The process is realized in the presence of a lubricating substance. After removal of the tool, the plastically deformed layer of metal around the hole is subjected to compressive hoop RSs after passing into a new elastic equilibrium due to the natural tendency of the elastically deformed layers to return to their original state. Therefore, the efficiency of the cold expansionprocess depends to a large extent on the thickness of the metal layer around the hole. Chronologically, the original idea of direct cold expansion via a spherical or conical-cylindrical mandrel was presented by Focke and Mize (1947) specifically for the treatment of holes in laminitic roller-sleeve chains. The authors used the concept of cold working, but the emphasis is not on the creating a zone with beneficialcompressive RSs, but on empirical dependencies to determine the required tightness and the forces required to drive the pins and bushings out of the holes.

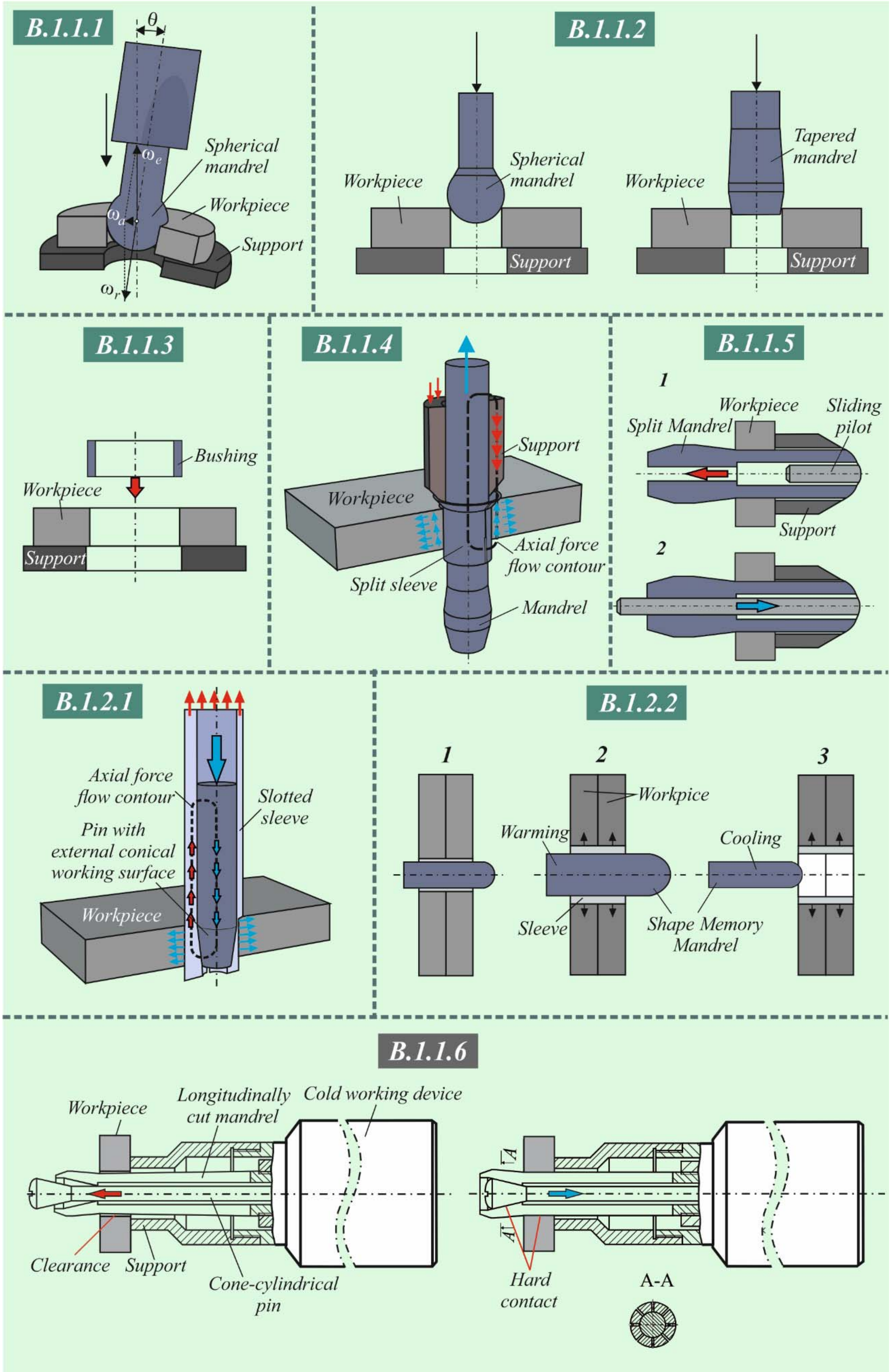

Fig. 3. Principle schemes of the static methods for introducing beneficial compressive RSs

The degree of cold expansion DCE is a quantitative indicator of the degree of cold work on the hole surface, which is numerically equal to the hoop linear strain for the points on its surface:

$$DCE = \varepsilon_{t,0} = \frac{d_t - d_0}{d_0} = \frac{i}{d_0} \times 100,\% \tag{2}$$

where d_t is the mandrel major diameter, d_0 is the diameter of the predrilled hole, and $i = d_t - d_0$ is the nominal tightness. The DCE is one of the main factors determining the distribution of RSs in a qualitative and quantitative aspect. For a particular material, the other important factors are: speed of movement of the mandrel, edge distance ratio e/D, D is the diameter of the hole, e is the distance from the center of the hole to the final undamaged edge of the plate (detail), the thickness of the plate, the initial diameter of the hole; stress sequence of adjacent multiple holes, thickness of the cut layer of metal in the final reaming (Su et al. 2023).

The main advantage of direct cold expansion methods is the simple-to-implement working scheme (Fig. 3, scheme B.1.1.2), because of that these methods are still applied nowadays as an effective approach to increase fatigue life. Direct cold expansion with a ball mandrel is applied significantly less often (Aid et al. 2014). Yan-li et al. (2017) reported that direct cold expansion, using tapered mandrel, increased the fatigue life of flat specimens made of 6061-T6 aluminum alloy 2.47 times compared to the conventional case of machined holes only by cutting. At the same time, these authors found that for all specimens with cold-expanded holes, the fatigue failure started at the hole edge on the entranceside. This confirms the well-known shortcoming of the methods with a tool passing through the hole (methods of group B.1.1): the presence of an axial gradient (Duncheva, 2017).

In order to minimize the axial gradient, Chakherlou et al. (2011) propose a cold expansion method, using a tapered pin with a mating tapered split sleeve. The resulting more uniform distribution of the hoop RSs leads to a greater efficiency of this method compared to the conventional variant of direct cold expansion with a conical-cylindrical mandrel. The positive effect of direct cold expansion of corrosion-damaged specimens made of 7B04-T6 Al-alloy sheet was experimentally establishedby Shuai et al (2019). The average fatigue life of specimens subjected to cold expansion with $DCE = 3.2\%$ is 2 times greater than the corroded specimens without cold expansion, and that of specimens treated with $DCE = 5.7\%$ is 3 times greater. The tendency to emphasize the microstructure in the vicinity of the stressed holes is also observed in relation to studies of the direct cold expansion process. According to Wang et al. (2021), the surface smoothing, surface compressive RSs field, and coldwork-hardened structure with the sub-grain refinement were responsible for increasing the fatigue life of the high-temperature low-cycle fatigue performance of the nickel-based superalloy hole structure. A major disadvantage of direct cold expansion methods is the need for two-sided access with respect to the front surfaces of the detail.

The interference fitting method consists in inserting a fastening element (sleeve, pin or bolt) with tightness into the pre-processed hole (Fig. 3, scheme B.1.1.3), and the same remains in the hole. As a result, the structural elements enter service with pre-stress hoopcompressive RSs around the hole (Chakherlou et al, 2011), which significantly reduces the stress amplitude due to the supporting effect of the fastener. As a result, fatigue lifewas increased (Lancotti and Polese, 2005; Chakherlou et al, 2013; Vallieres and DuQuesnay, 2014). Huang et al. (2017) applied a combined approach involving sequential direct cold expansion using tapered mandrel and bushing interference fitting with respect to aluminum-lithium lugs. This approach provides up to 4.4 times greater fatigue life compared to the conventional case without stressing the holes.Zhang and Zuo, (2024) investigated the influence of the interference fit size (including presence of clearance) on the fatigue behavior of 7050-7451 aluminum alloy plate and steel pin. They found that increasing the interference fit size leads to a shift of the crack initiation location from the edge of the hole to the loading direction, and the high interference size worsens the fatigue behavior. Using MSC NASTRAN/PATRAN FEM software, Chikmath et al. (2018) predict the fatigue life of lug joints with fasteners. Based on an experimental and finite element study (Liu et al, 2020) it was found that direct cold expansion (using tapered mandrel) increases the fatigue life of bolt holes of nickel based superalloy compressor disk for an aircraft engine by 2.1-3.5 times in the region of small-cycle fatigue at an elevated temperature of $600°C$. Wang et al. (2024) propose a new dynamic method for installing interference bolts in composite bolted structures in order to reduce the damage common to the traditional static method for installing interference bolts in composite bolted structures. The proposed dynamic method provides about 4 times greater fatigue life compared to the static method and 38 times greater fatigue life than that of specimens without stressing the holes.

The split sleeve cold expansion (SSCE) method (Fig. 3, scheme B.1.1.4) is the most widely used method of group B.1 in engineering practice. It is a development of the pioneering method (Champoux, 1971), which is based on the use of a thin-walled elastic longitudinally cut intermediate sleeve of stainless steel with internal lubrication, through which a conical-cylindrical mandrel is drawn. The sleeve is placed around the mandrel and together with it is introduced into the hole. The hole expands as the mandrel is drawn back through the cut sleeve, causing plastic deformation around the hole and elastic deformation in the more distant layers. During the cold expansion process, the cut sleeve contacts a support, causing an axial force flow to pass through the detail. This axial force flow causes a significant axial gradient in the RSs distribution.

The SSCE method is currently owned by Fatigue Technology Inc. (Quincey et al., 1994) in which the cut disposable sleeve is automatically withdrawn from the treated hole. The use of an intermediate sleeve with internal lubrication reduces the necessary axial force when pulling the mandrel and allows the process to be realized with one-sided access to the processed plate. A major disadvantage of the SSCE method is the expensive intermediate sleeve, which after removal from the hole is discarded, as it is unsuitable for reuse. Based on SSCE, Fatigue Technology Inc. has developed the RailTec system for cold expansion the rail-end-bolt holes. As a result, the service life of the rails before the appearance of fatigue cracks increases 3-10 times, which is reflected in significantly greater safety and reduced costs of ongoing maintenance. Using a combined approach based on strain gauge experiment and FEM, Pucillo et al. (2021) predict the stresses around cold-expanded rail holes and develop a crack growth simulation model.

The effectiveness of SSCE to introduce useful compressive RSs in correlation with increasing the fatigue life of various nonferrous alloys (aluminum, magnesium, titanium) typical of the aerospace industry has been experimentally investigated innumber of publications. For 7050 aluminum alloy, Li et al. (2022) found that SSCE provided the most favorable RSs for $DCE = 4\%$, which increased the fatigue life by up to 3 times compared to the conventional case of unstressed holes. 7B04-T651 sheet high strength aluminum alloy is used for making load-bearing structures in airplanes, such as wings, panels and frames. For this alloy, the effect of SSCE for $DCE = 5\%$ has been proven based on fatigue tests on specimens with stressed and unstressed holes (Wang et al, 2019).

The process of cyclic loading is accompanied by a continuous redistribution of the hoop RSs introduced through SSCE, and fatigue cracks mostly initiate from the mandrel entrance side, where subsequently residual hoop stresses begin to relax considerably (Ozdemir, 2018). SSCE increases the fatigue life of TC4 titanium alloy open hole up to 1.5–3.0 times (Yuan et al, 2015). Based on fatigue tests, it was found that $DCE = 6\%$ is an optimal value for AZ31B rolled magnesium alloy, and the effect of SSCE is more pronounced in the multicycle fatigue area (Faghih et al, 2023). Amjad et al. (2016) compared the effect of SSCE in thick and thin plates. The thin specimens (thickness of 1.6 mm) experience a combination of general bending, significant local buckling, and a noticeable surface upset effect, while the thicker specimens (thickness of 6.35 mm) show no general bending.

A significant number of scientific publications are based on 3D FEM of SSCE to evaluate the influence of various process parameters in correlation with the RSs field. Based on 3D simulations, Li et al. (2022) found that the RSs in 7050 aluminum alloy were most favorable for $DCE = 4\%$, and fatigue tests showed 3 times greater fatigue life compared to unstressed holes. Through parametric studies based on 3D FEM of the SSCE, Dey et al. (2021, 2022) evaluate the influence of the friction coefficient between the split sleeve and mandrel, DCE, material's yield strength on mandrel pulling force and RSs. Numerical results show that an increase in the friction coefficient reduces the useful hoop RSs on the mandrel entrance side, which increases the risk of fatigue crack initiation around the hole edge. The results of numerical simulations conducted by Liu et al. (2021) on 7075 aluminum alloy showed that as DCE increases, compressive hoop RSs, mandrel pullout force, and fatigue life increase.

Gao et al. (2023) developed a 3D FEM on SSCE of Ti-Al stacked joint holes structure. These authors investigated the implementation sequence of SSCE, DCE, the coefficient of friction between the sheets and the length/diameter ratio of the holes. The results show that when the SSCE process is realized with $DCE = 5.2 - 5.6\%$ first for the Ti sheet, more favorable RSs are introduced. Based on a comparison between the results of numerical simulations and experimental results, the axial gradient of the hoop RSs introduced after SSCE in 7075 aluminum alloy has been confirmed: the compressive stresses are the largest in the middle layer and the smallest on the mandrel entrance side (Zhang et al, 2020). Using Abaqus/CAE, Liu et al, (2022) developed a 3D FEM to investigate the RSs field in 6061 aluminum alloy plate depending on the reaming depths after SSCE. The authors calculated the fatigue life using the fatigue analysis software FE-SAFE and verified by fatigue tests. The fatigue life increased with increasing reaming depth, and the best result was obtained when the reaming depth was 0.5 mm. Lv et al. (2023) investigate the RSs distribution and variation along the hole edges of 7075 aluminum alloy single-hole and multi-hole split sleeve cold expansion specimens. From the perspective of the axial gradient, it is clear that 2D FEMs do not provide a sufficiently realistic picture of the distribution of the introduced RSs (Kumar and Badu, 2017). The use of a pseudo-2D axisymmetric FEM involves a certain compromise in modeling given the longitudinally cut sleeve. Based on comparison with experimental results, Achard et al, (2016) developed such a model by investigating the effect of high DCE values on Ti-6Al-4V alloy. Fatigue tests performed confirm the effect of SSCE for this alloy.

As explained above, the RSs introduced by the methods of subgroup B.1.1 are characterized by a significant axial gradient due to the three-dimensional deformation process. On the other hand, the use of a longitudinallysplitsleeve in SSCE reflects in an inhomogeneous distribution of RSs in a hoop direction, characterized by a heart shape (Li et al, 2022). The initially introduced RSs do not remain stable during dynamic/cyclic loading due to the relaxation effect. This phenomenon is most strongly manifested in the conditions of low-cycle fatigue due to several mechanisms: 1). Creep at elevated temperature; 2). Development of cracks in a field of tensile RSs; 3). Accumulation of plastic deformation under cyclic loading; 4). Plastic deformation caused by exceeding the macroscopic yield strength (static relaxation) (Jones and Bush, 2017). A theoretical-experimental approach to modeling time-dependent creep and residual stress relaxation around cold worked holes in aluminum alloys at room temperature was developed by Maximov et al, (2014).

Recently, research related to cold expansion is not limited to the study of RSs and fatigue behavior. There is a trend towards more in-depth studies of the effect on the microstructure. For example, in samples of 7075-T6 aluminum alloy, after SSCE, in addition to the high compressive RSs, the high-strength nanocrystals on the surface of holes and the excellent resistance to strain localization of the gradient structure are observed (Wang et al, 2023). These factors increase the high-cycle fatigue life by 9 times. The application of SSCE in relation to AZ31B sheet with $DCE = 5$ leads to 3 times greater fatigue life compared to the conventional case due to microstructural changes, greater stiffness at the base of the notch and compressive RSs (Faghih et al, 2020).

The split mandrel cold working (SMCW) method was developed by West Coast Ind. as an alternative to the competitive SSCE method for application in the aerospace industry (Hogenhout, 1986). At its coreis the idea of eliminating the costly longitudinally cut sleeve for single use. The SMCW utilizes a hollow, tapered mandrel that is longitudinally slotted into quarters with a sliding pilot cylindrical shaft extending through the mandrel cylindrical hole, which serves to solidify the mandrel prior to cold working the detail (Fig. 3, scheme B.1.1.4). With the pilot retracted, the mandrel is partially collapsible, allowing insertion into the pre-drilled hole. When the puller unit is actuated, the pilot extends through the mandrel's cylindrical hole, which solidifies. The solidified mandrel is then pulled through the hole, plastically deforming the surrounding material and creating a field with compressive RSs. Comparative analyzes between the split sleeve and split mandrel methods have shown the advantages of the split mandrel over the split sleeve method (Rodman and Creager, 1994; https://coldwork.com/images/pdfs/SM_Tooling.pdf).

Eliminating the split sleeve results in the following additional advantages of the SMCW method: 1). Elimination of several steps in the technological cycle; 2). A significant reduction in the time required to stress a hole; 3). Reduced direct and indirect costs associated with manufacturing and shipping the disposable cut sleeve (Leon, 1998a).

Using FEM and experimental approach, Jang et al (2008) compared the RSs field and fatigue life of 6061-T6 aluminum alloy specimens with and without chamfers fabricated prior to cold expansion by means of SMCW. The authors report that stressed chamfered holes show improved fatigue life compared to non-chamfered holes due to redistribution of RSs. Liu et al, (2023) developed a 3D FEM for the effect of SMCW on the field of RSs in 7050 aluminum alloy for three cases of hole stressing: single, double one-way and double two-way. They found that double two-way stressing resulted in larger compressive and uniform RSs and hence the greatest increase in fatigue life – 1.8 times greater compared to unstressed holes, while after single stressing the increase was 1.52 times and after double one-way – 1.73 times.

A main advantage of the SSCE and SMCW methods is that they are implemented with one-way access, i.e. require access only from one side of the plate, resp. one operator is required. These methods allow for relatively fast technological cycles and enable the automation of assembly operations. The ability to implement cold expansion processes with one-sided access is of decisive importance in the aerospace industry, where the relevant elements have a very large number of holes and are of large dimensions. Besides the axial gradient in the stressed and strained state inherent to the methods of subgroup B.1.1, the SSCE and SMCW methods are characterized by the following main disadvantages: 1). The technological cycles corresponding to both methods contain large number of operations – in the SSCE method the total number of operations is 13, and in the SMCW method – 11. 2). A very tight tolerance on the diameter of the pre-machined holes is required; 3). The use of the support corresponds to fixing the plate, analogous to the "three-point bending" scheme, which causes the plate to bend around the hole. 4). Disadvantages 1) and 2) lead to a significant increase in the cost of the complete technological process.These disadvantages are a direct consequence of the essentially identical concepts of the two methods: the *DCE* of the hole depends only on the diametrical dimensions of the mandrel for SSCE or of the mandrel and pin for SMCW, and the diameter of the predrilled and reamed hole. In order to guarantee the specified tightness between the deforming mandrel and the pre-drilled hole, it is necessary to carry out control according to a geometric criterion, both of the diameter of the pre-drilled hole and of the working part of the "hardened" mandrel for wear assessment (by gauges). Such control is also performed on the mandrel hole of which the cylindrical pin is positioned in the SMCW method.

A new modified method based on SMCW was invented to eliminate the above-mentioned disadvantages 1) and 2) (Maximov and Duncheva, 2014). Unlike SMCW, the modified split mandrel cold working method does not require a tight tolerance on the diameter of the pre-drilled holes. The modified method involves a longitudinally cut hollow mandrel with a central hole with a conical surface (which is suitably profiled) (Fig. 1.3, scheme B.1.6). An axially movable conical cylindrical pin with an outer conical surface (which is profiled in the same way as the conical surface of the hole in the hollow mandrel) is positioned in this hole. The two conical surfaces (of the hole and of the pin) have the same angle of inclination and widen in the direction of the cut end of the mandrel.After introducing the longitudinally cut mandrel into the drilled hole, the pin is moved axially until the two conical surfaces touch and tight contact is ensured between them. In this position, the cylindrical surface of the hardened mandrel contacts that of the pre-drilled hole. This ensures constant pressure regardless of the relatively wider tolerance of the pre-drilled holes and creates conditions for eliminating four steps from the technological cycle for realizing SMCW: countersinking of the drilled hole to ensure the corresponding initial hole diameter; control of the initial diameter of the hole with a caliber; control of the working part of the mandrel to assess its wear; cold expanded hole control with caliber.The presence of tight contact guarantees constant tightness, since the latter is determined by two diametrical dimensions of the mandrel - the maximum diameter of the cylindrical working part and the diameter of the cylindrical surface contacting tightly with the surface of the hole (Fig. 1.3, scheme B.1.6). The effectiveness of the new method for increasing the fatigue life of 2024 aluminum alloy in the conditions of a relatively wide tolerance of pre-drilled holes has been experimentally proven on the basis of a developed hydraulic device (Maximov et al, 2024).

The static methods of subgroup B.1.2 enable the minimization of the axial gradient in the RSs distribution and the unwanted surface upset effect, becausethese methods are based on the concept of static radial impact on the entire surface of the hole. The concept of "pure" radial cold expansion excludes tangential contact between the tool and the surface of the hole, as well as the presence of support(s). Even in the ideal case of "pure" radial expansion, full axial symmetry in the geometry of the structural elements and a perfectly homogeneous material, an axially uniform zone of RSs cannot be achieved. The reason is the difference in the radial stiffness of the different cross-sections of the plate: the radial stiffness is the greatest in the middle plane, and the smallest in the two end sections. The idea of "pure" radial expansion was used in the invention of a method using a shape memory material mandrel (Kennedy and Larson, 1993). The mandrel expands radially, widening the hole by means of an intermediate sleeve, then shrinks (Fig. 3, scheme B.1.2.2). This transformation in its size is achieved by successive heating and cooling. After the mandrel is removed, the sleeve remains in the hole, so the radial expansion on the hole remains. Temperature impact by heating causes relaxation of the introduced RSs, reducing their beneficial effect.To avoid this undesirable effect, Kuo (2001) proposed a method that relies on a superelastic material. The practical implementation of these methods is associated with great technological difficulties. Therefore, to minimize the axial gradient, the most promising for practical implementation are the methods in which the radial expansion is achieved by means of multiple radially movable working membersWolcken et al. (2009) developed this idea to the level of a “schematic diagram of a hand-operated tool”, emphasizing the rigid connection between an axially moving conical or pyramidal mandrel and radially moving multiple sectors. It is clear that the *DCE* is directly dependent on the axial displacement of the mandrel. Regardless of the mentioned invention of Wolcken et al., Maximov and Duncheva, (2011) invented a “Tool for machining fastener holes”, later developing the invention further (Maximov and Duncheva, 2014). The method is named by the authors "Symmetric cold expansion" (Fig. 3, scheme B.1.2.1).The conducted in-depth FEM and experimental studies (Maximov et al, 2013; Maximov et al, 2014) confirm that the "Symmetric cold expansion" imparts beneficial near-uniform hoop RSs around the hole along its axis having a minimized and symmetric gradient with respect to the plate middle plane. The RSs in the novel method are much more uniformly distributed in comparison with the methods from group B.1.1. On the basis of fatigue tests, the greater efficiency of the new method in the highcycle fatigue field has been proven. Based on the "Symmetric cold expansion" method, an approach for multi-objective optimization of the cold expansion of rail-end-bolt holeshas been developed (Duncheva and Maximov, 2013). The approach is based on a generalized 3D FEM of the rail bolted joint, in which the assembly stresses are also taken into account. After "Symmetric cold expansion" process simulation at certain optimum DCE, the cold expansion beneficial effect has been proven.

3.2.2. Dynamic methods (group B.2)

According to the way of applying the dynamic impact, the methods of group B.2 are (Fig. 1): 1). Contact (by mechanical impact) (subgroup B.2.1) and 2). Non-contact (by radial pulsating electromagnetic force) (subgroup B.2.2). In turn, contact methods are based on the following two types of dynamic impact sources: mechanical impact or pulsation (Fig.1, B.2.1.1, B.2.1.2, B.2.1.3.1); by electromagnetic drive (Fig.1, B.2.1.4, B.2.1.3.2).

The concept of stressing the material around the holes by mechanical impact was developed for application to relatively thin sheet components because the impact is applied to the front surfaces. In the "Ring groove coining" (Fig. 4, scheme B.2.1.1) and "Pad coining" (Fig. 4, scheme B.2.1.2) methods, impact is applied after drilling the holes. The pioneering idea (Phillips, 1963) consists of punching or pressing a thin channel of semicircular cross-section on the faces of metal components in close proximity around the periphery of circular or non-circular openings. The method is known as "Stress coining" because for the first time the effectiveness of the method ("Ring groove coining") is justified by the effect of the introduced around the hole beneficialhoop compressive RSs to prevent the development of type I fatigue cracks. The basis of the "Pad coining" method (Phillips, 1974; Phillips, 1975) is the use of indenters with an annular cross-section in the direction of the axis of the hole, so that one indenter performs the function of a Poisson, and the other - a matrix. The effectiveness of methods B.2.1.1 and B.2.1.2 in relation to aluminum alloys 2014-T3 and 7075-T6 has been confirmed by fatigue tests in the inventions themselves, and scientific publications devoted to "Stress coining" methods are episodic (Speakman, 1970).

The StressWave method (Easterbrook, 2001) was developed as an alternative to the SSCE and SMCW methods for application in the aerospace industry. The method is implemented in two stages (Fig.4, scheme B.2.1.3.1): 1). Creation of a compressive zone in the dense material by an impact on both sides of the plate simultaneously along the axis of the future hole, which provokes plastic deformation in the impact zone and an elastic wave of stresses in all directions; 2). Drilling of the hole, resulting in a redistribution of RSs in the direction of increasing hoop compressive stresses around the periphery of the hole. Conducted FEM and experimental studies of the method confirm its greater efficiency in terms of beneficial RSs and fatigue life of 7085-T7651 and 7050-T7451plates compared to the competitive SSCE method (Easterbrook and Landy, 2009). Based on fatigue and crack propagation tests on 7075-T73 aluminum alloy specimens Boniet al, (2013) found that StressWave leads to an improvement in fatigue behavior comparable to that after applying the SSCE process twice on the same hole. The wider use of the StressWave method is limited by the technological difficulties arising from its principle scheme.

Zheng et al (2022) propose a new StressWave method based on electromagnetic force. The method allows controlling the maximum force value with excellent repeatability. The equivalent speed generated by the electromagnetic drive reaches $DCE4-8\,m/s$, and the strain rate of 10^2-10^4. The method is implemented by a pin directed to a small pre-hole (diameter of 2 mm) for positioning, driving the pin, applying a shock load within a few milliseconds until an indentation is formed, after which a 6 mm diameter hole is drilled in its center. Experimental results show that the new double-side StressWave process (Fig. 4, scheme B.2.1.3.2) leads to a significant increase in fatigue life and reduced hardness degradation compared to direct cold expansion.

The idea of electromagnetic drive was used by Guo et al, (2021), who presented a new dynamic method for direct cold expansion using a conical-cylindrical mandrel (Fig. 4, scheme B.2.1.4). Comparison with the conventional static method for 6061-T6 aluminum alloy specimens shows that the dynamic method reduces resistance to hole expansion, results in less deviation from cylindricity, and exhibits greater fatigue life, especially at larger load amplitudes. The same authors extend the research of the new dynamic method in the aspect of studying the mechanisms for increasing the fatigue life. They found that the greater efficiency of the dynamic method is due to the larger compressive RSs on the mandrel entrance side, and hence to the occurrence of fatigue cracks in different sources that develop in the horizontal direction (Guo et al, 2021).

The methods shown in Fig. 4, schemes B.2.2.1 and B.2.2.2, implement the idea of a dynamic non-contact process of cold expansion using a radial pulsed electromagnetic force. The methods are intended for sheet components in aircraft construction. The method developed by Zhou et al, (2017) was pioneered, designed and implemented using two external and two internal coils, symmetrically located with respect to the upper and lower surfaces of the sheet component (Fig. 4, scheme B.2.2.1). For 2A12-T4 aluminum alloy sheet specimens, the dynamic non-contact process was found to double the fatigue life at maximum stress compared to the conventional mechanical static cold expansion process. This result is due to the non-contact principle of impact and the more uniform distribution of the introduced RSs. The effectiveness of the non-contact method with two-stage coils in terms of fatigue behavior has been confirmed by the experimental and FEM studies of thin plates of the specified aluminum alloy (thickness of 1.5 mm) conducted by Xu et al. (2022). The fatigue life of the fasteners processed by the electromagnetic method is 1.77 times greater than that obtained after the conventional direct mandrel cold expansion method at the maximum applied stress of 120 MPa.

Geng et al. (2022) propose a modified simplified method for non-contact electromagnetic cold hole expansion using a single coil (Fig. 4, scheme B.2.2.2). Fatigue test results of 2A12-T4 aluminum alloy specimens show a good combination of SI characteristics, a fine structure near the hole surface and significant improvements in fatigue behavior. Disadvantages of dynamic contactless methods are: 1). Need for sophisticated specialized equipment; 2). Relatively accurate centering of the treated hole; 3). Thickness limit for sheet components.

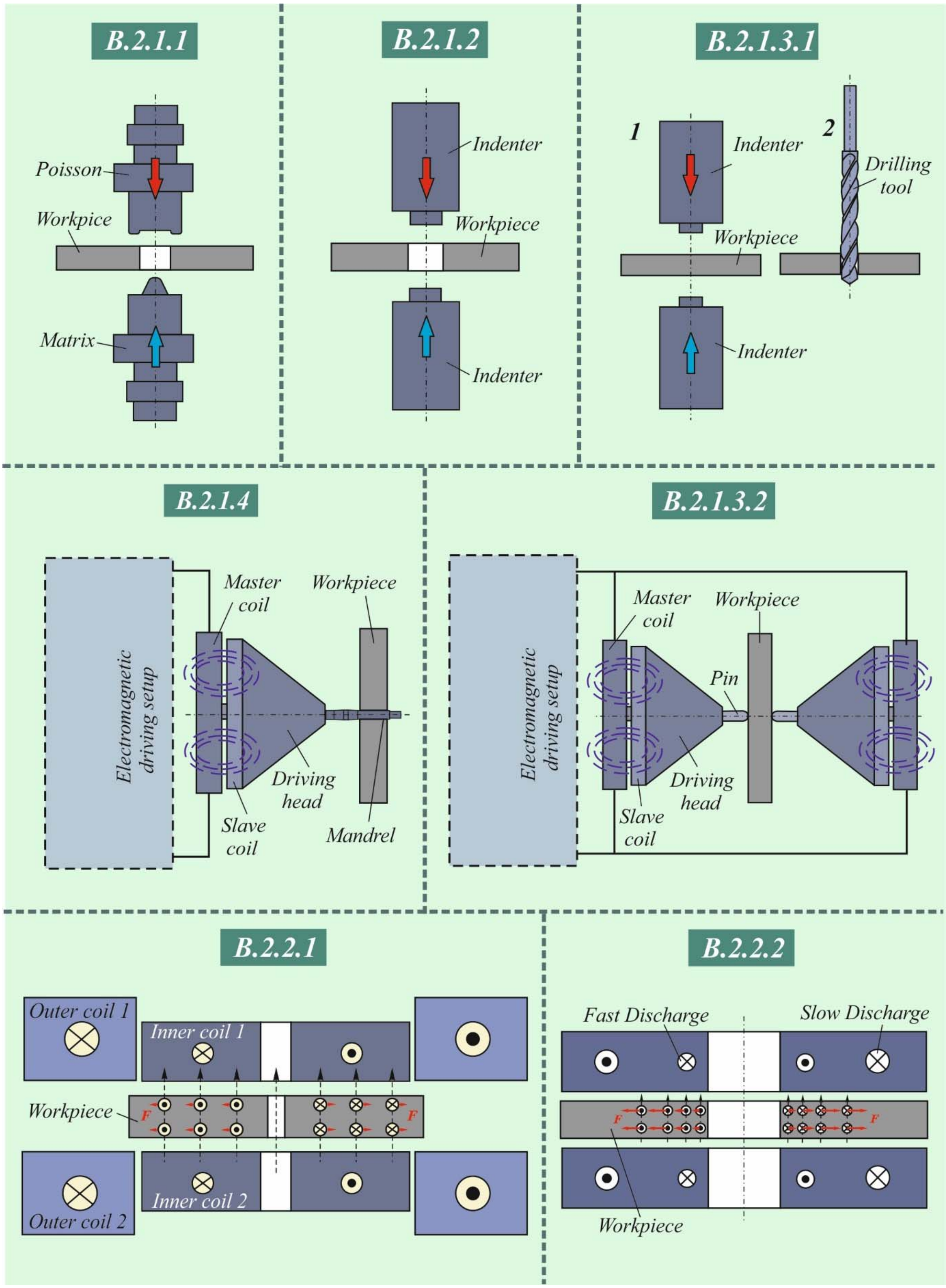

Fig. 4. Principle schemes of the dynamic methods for introducing beneficial compressive RSs

3.3. Methods for introducing beneficial hoop compressive RSs and improving in SI

The methods of group C (Fig. 1) simultaneously aim at two effects: 1). Introduction of beneficial hoop RSs; 2). Modification of the complex state of the material (SI) around the holes. For this purpose, the methods of this group have a common physical basis: tangential contact existsbetween the corresponding tools and the hole surface in both axial and hoop directions. Therefore, the kinematics of the corresponding tools include rotation around the hole axis and translation along this axis. The schematic diagrams of the methods of group C are shown in Fig. 5.

3.3.1. Method using deforming tool with K-profile (C.1)

Maximov et al. (2019) developed a method and tool for finishing large number of small fastener holes in high-strength aluminum alloy structures used in aircraft construction. The cross-section of the deforming part of the tool is specially profiled so that the contact with the surface of the hole is interrupted. The difference between the diameter D of the circle described around the deforming part of the tool (Fig. 5, scheme C.1) and the diameter of the hole d_0 obtained after reaming provides the necessary tightness i, without which the process of cold plastic deformation is impossible. To "cold expand" the hole, the tightness i must be greater than the initial roughness height, estimated by the hole roughness parameter R_z. At the same time, to ensure discontinuous contact in the cross-section, the condition $d_0 > d$ must be met, where d is the diameter of the circle inscribed in the contour of the cross-section of the deforming part of the tool. Therefore, the method is effective if the geometric condition is met (Maximov et al, 2019):

$$D - R_z > d_0 > d \ . \tag{3}$$

The tool geometry is designed for unidirectional rotation, with the edges of the deforming part having a radius r. For the described geometry and kinematics, the deforming parts of the tool edges cause surface cold working, creating a rotating deformation wave. Each point on the surface of the treated hole is repeatedly subjected to the impact of the deforming edges, which is a prerequisite for significant equivalent plastic strain of the surface layer. The discontinuous contact in the cross-section allows the lubricant to reach any point on the surface of the hole, which is a prerequisite for a favorable smoothing effect. The modification of the microstructure is due to the sliding frictional contact between the deforming part of the tool and hole surface. Thus, this method produces three beneficial effects: 1). Cold expansion of the hole, resp. introduction of beneficial district compressive RSs; 2). Surface cold working, resp. strain hardening; 3). Modification of the microstructure. These three effects have been investigated and confirmed by experiment and 3D FEM simulations. The obtained S–N curves prove that the fatigue life of specimens made of 2024-T3 aluminum alloy increases significantly compared to the case of only drilled and reamed holes.

3.3.2. Friction Stir Cold Expansion (C.2)

A new concept for improving the fatigue behavior of a large number of fastener holes in aircraft structural elements is developed by Duncheva et al, (2017). The concept is based on a new method which combines the advantages of cold expansion with the Friction Stir Processing technique, which is effective for application on aluminum and magnesium alloys (Mishra et al, 2003). On this basis, the method is called Friction Stir Hole Expansion. According to the principle scheme of the method (Fig. 5, scheme C.2), the tool is driven by the machine spindle, performing simultaneous rotation around its axis and rectilinear translation along the axis of the hole with feed f. The working part of the tool contains conical and cylindrical sections. The work cycle includes straight and reverse stroke of the tool, with the straight stroke ending when the intersection between the conical and cylindrical sections passes a few millimeters past the exit side of the hole. The reverse stroke is performed with the same direction of rotation of the tool.The method leads to the following two effects: 1). A macro-effect resulting in the creation of a field of compressive RSs at a relatively greater depth. This effect is a consequence of the plastic deformation, low strain rate, and the lower-than-recrystallization temperature in the outer layers around the hole surface; 2). A micro-effect (Stir effect), expressed in the modification of the microstructure near the hole in the direction of grain refinement, homogenization and reduction of pores in the material. The increased local temperature immediately around the hole causes a "softening effect" in the material, which significantly reduces the technological resistance, resp. the resistive force and torque applied to the tool decreases. The effectiveness of the method has been evaluated by fatigue tests and 3D thermomechanical FE analysis to evaluate the macro-effect (Duncheva et al, 2017). For 2024-T3 aluminum alloy specimens, it has been shown that the greater fatigue life of fastener holes machined by Friction Stir Hole Expansion is largely due to the resulting micro-effect. The Friction Stir Hole Expansion method reduces labor costs and machining time, and hence reduces the total cost of machining large number of holes in aluminum alloy structural members.

3.3.3. Hertz Contact Rotary Expansion (group C.3)

Group C.3 methods (techniques) were developed specifically for treating holes in superalloy components. The basis of these methods is the idea of modifying the microstructure around the hole using a tool whose working part is subjected to laser texturing. The aim is to achieve a hardened surface and a specific surface morphology characterized by small hemispherical protrusions. The described morphology provides "hertz contact" with the surface of the hole, which is why the name of the chronologically first method of this group is adopted in the generalized classification scheme - "Hertz contact rotary expansion process" (Cao et al, 2020). This technique acts on the hole through the rotary extruding movements of the tool, including the stiffened sleeve and conical mandrel (Fig. 5, scheme C.3.1).The proposed technique significantly improves hole SI due to grain refinement near the hole surface and introduction of compressive RSs at greater depth in rolled nickel-based GH4169 superalloy.

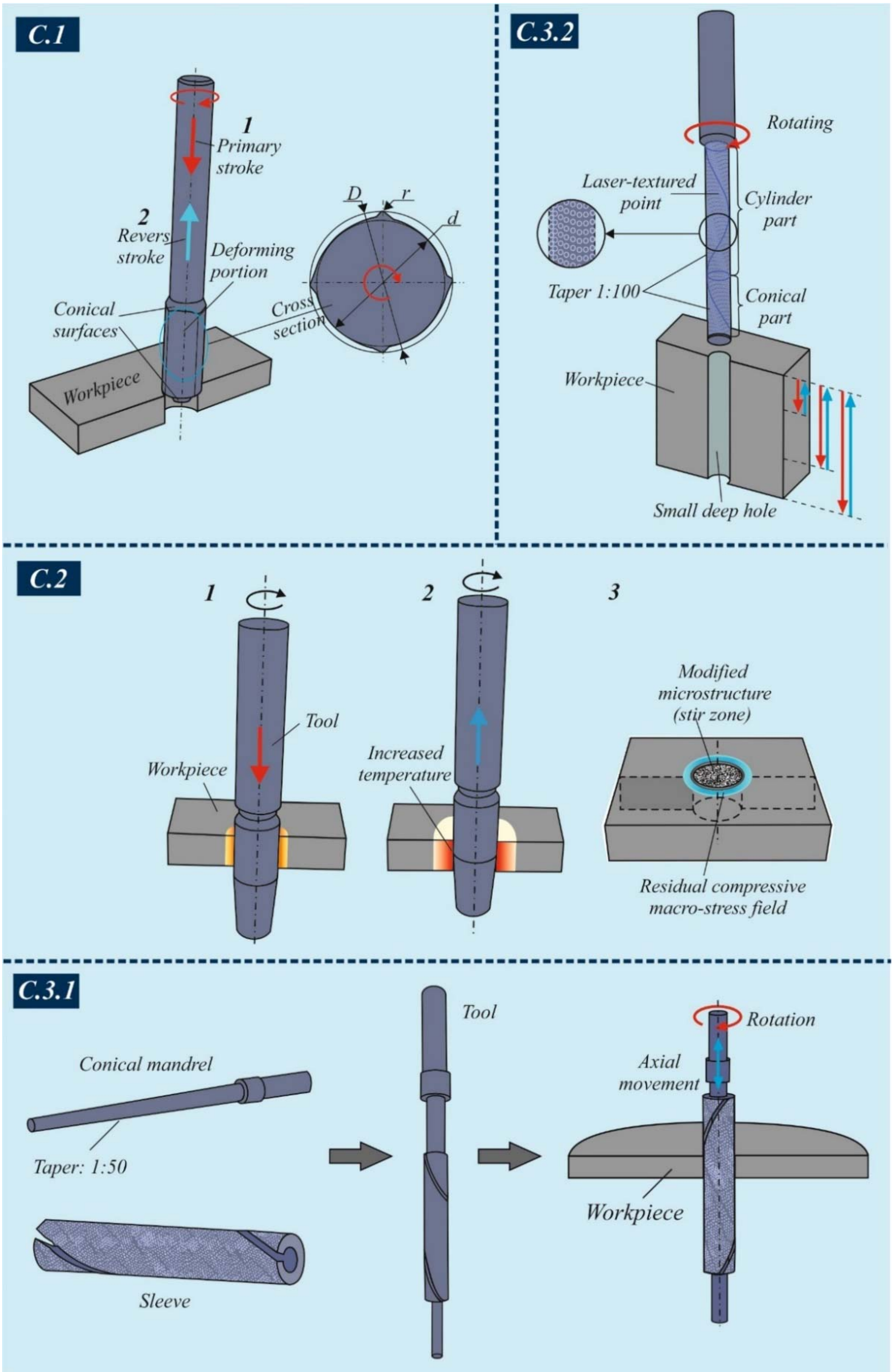

Fig. 5. Principle schemes of the methodsfor introducing beneficial hoop compressive RSs and improving in SI

Yao et al. (2022) developed a new technique for cold expansion of small deep holes (diameter less than 2 mm and depth greater than 10 mm), called by the authors "Multi-spherical bump rotating cold expansion process". The key element in this technique is the tool with large number of spherical protrusions obtained after laser texturing (Fig. 5, scheme C.3.2). The authors investigated the effect of the method by applying different DCE ($DCE = 2.1\%, 2.6\%, 3.1\%$) to small deep hole specimens of Inconel 718. Compared to a reamed hole only, the hole treated with the new technique with different values of DCE, is characterized by a formed plastically deformed layer with a maximum depth of $32.73 - 85.54\,\mu m$, a minimum surface roughness $R_a = 0.115 - 0.138\,\mu m$ and a depth of the zone with compressive RSs $0.39 - 1.077\,mm$. At the same time, the fatigue life at $400°C$ was increased by an average of 3.66 and 8.05 times for $DCE = 2.1\%$ and $DCE = 2.6\%$, respectively.

4. CONCLUSION

A generalized classification scheme of established in engineering practice and new methods for increasing the fatigue life of metal structural elements with fastening holes has been developed. The systematization of the methods in the generalized classification scheme is based on the following three main approaches for modifying the material around the openings: 1). Surface Cold Working; 2). Introducing of beneficial compressive hoop RSs; 3). Introducing beneficial compressive hoop RSs and improving in SI. In accordance with their principle schemes, an analysis of the different groups of methods was made from the point of view of their functional capabilities and in a technological aspect.

REFERENCES

Abdelkrim Aid, Zahar Semari, Mohamed Benguediab. Finite Element Method Investigation of the Effect of Cold Expansion Process on Fatigue Crack Growth in 6082 Aluminum Alloy. Modeling and Numerical Simulation of Material Science 4 (2014) 25-31

Achard V., Daidie A., Paredes M., Chirol C. Cold expansion process on hard alloy holes-experimental and numerical evaluation. Mechanics & Industry 17 (2016) 303 DOI: 10.1051/meca/2015075

Achintha M., Nowell D., Fufari D., Sackett E.E., Bache M.R. Fatigue behaviour of geometric features subjected to laser shock peening: Experiments and modellingInternational Journal of Fatigue 62 (2014) 171–179

Aid A., Semari Z., Benguediab M. Finite Element Method Investigation of the Effect of Cold Expansion Process on Fatigue Crack Growth in 6082 Aluminum Alloy. Modeling and Numerical Simulation of Material Science 4 (2014) 25-31 doi: 10.4236/mnsms.2014.41005

Amjad K., Wang W-C., Patterson E. A comparison of split sleeve cold expansion in thick and thin plates. The Journal of Strain Analysis for Engineering Design.;51(5) (2016) 375-386 doi:10.1177/0309324716642621

Bliumberg V.A., Glushtenko V.F. Which solution is better? Leningrad, Lenizdat (in Russian) (1982)

Boni L., Fanteria D., Lanciotti A., Polese C. Experimental and analytical assessment of fatigue and crack propagation in cold worked open hole specimens. Fatigue & Fracture of Engineering Materials & Structures 36(9) (2013) 930-941 DOI: 10.1111/ffe.12050

Cao X., Zhang P., Liu S., Lei X.L., Wang R.Z., Zhang X.C., Tu S.T. A novel hole cold-expansion method and its effect on surface integrity of nickel-based superalloy. J. Mater. Sci. Technol. 59 (2020) 129–137

Chakherlou T. N., Vogwell J., A novel method of cold expansion which creates near-uniform compressive tangential stress around a fastener holes. Fatigue Fract Engng Mater Struct 27 (2004) 343-351

Chakherlou T.N., Taghizadeh H., Aghdam A.B. Experimental and numerical comparison of cold expansion and interference fit methods in improving fatigue life of holed plate in double shear lap joints. Aerospace Science and Technology 29 (1) (2013) 351–362

Chakherlou T.N., Razavi M.J., Aghdam A.B., Abazadeh B. An experimental investigationof the bolt clamping force and friction effect on the fatigue behavior of aluminum alloy 2024-T3 double shear lap joint. Mater. Des. 32 (2011) 4641–4649

Champoux L.A. Coldworking Method and Apparatus. USA Patent 3566662, Patented March 2 (1971)

Champoux R.L. Apparatus for prestressing fastener holes. USA Patent 4524600, Patented June 25 (1985)

Champoux R.L. Apparatus having extended prestressing and sleeve retaining devices for prestressing countersunk fastener holes and method. USA Patent 4471643, Patented Sep. 18, (1984)

Chikmath L., Ramanath M.N., Dattaguru B. Fatigue Life Benefits of Cold Worked Holes in Fastener Joints. Procedia Structural Integrity 14 (2019) 922–929

Dey M.K., Kim D., Tan H. Finite element parametric study of the split sleeve cold expansion on residual stresses and pulling force. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science. 236 (5) (2022) 2447-2461 doi:10.1177/09544062211025563

Dey M.K., Kim D., Tan H. Effect of Friction on Residual Stress Distribution Induced by Split Sleeve Cold Expansion Process. International Mechanical Engineering Congress & Exposition (2021) doi.org/10.1115/IMECE2020-24240

Duncheva G.V., Maximov J.T. A new approach to enhancemenet of fatigue life of rail-end-bolt holes. Eng Fail Anal 29 (2013) 167-179

Duncheva G.V., Maximov J.T., Ganev N. A new conception for enhancement of fatigue life of large number of fastener holes in aircraft structures. Fatigue Fract Eng Mater Struct 40(2) (2017) 176-189

Duncheva G.V. Synthesis and optimization of methods for increasing the fatigue life of metal structural elements with holes. Dissertation for obtaining the scientific degree "Doctor of Sciences", Gabrovo (in Bulgarian) (2017)

Duncheva G.V., Maximov J.T., Anchev A.P., Dunchev V.D., Argirov Y.B., Kandeva-Ivanova M. Enhancement of the wear resistance of CuAl9Fe4 sliding bearing bushings via diamond burnishing. Wear 510-511 204491 (2022)

Duncheva G.V., Maximov J.T., Anchev A.P., Dunchev V.P., Argirov Y.B. Multi-objective optimization of internal diamond burnishing process. Material and Manufacturing Processes, 37 (4) (2022) 428-436

Easterbrook E.T. Method and apparatus for producing beneficial stresses around apertures by use of focused stress waves. USA Patent 6230537, Patented May 15 (2001)

Easterbrook E.T., Landy M.A. (2009) Evaluation of the StressWave cold working (SWCW) process on high-strensth aluminum alloys for aerospace (2009)

Ecoroll–http://teco.net.au/-pdf/-ecoroll/-ecoroll-catalog_en_web.pdf

Faghih S., Shaha S.K, Behravesh S.B, Jahed H. Split sleeve cold expansion of AZ31B sheet: Microstructure, texture and residual stress. Mater. Des. 186 108213 (2020)

Faghih S., Behravesh S.B., Shaha S.K., Jahed H. Effect of split sleeve cold expansion on fatigue and fracture of rolled AZ31B magnesium alloy. Theoretical and Applied Fracture Mechanics 123 103715 (2023) https://doi.org/10.1016/j.tafmec.2022.103715

Gao Y., Lu S., Fu J. Numerical Simulation Investigation on Split Sleeve Cold Expansion of Ti-Al Stacked Structure. J. Wuhan Univ. Technol.-Mat. Sci. Edit. 38 (2023) 1147–1154 https://doi.org/10.1007/s11595-023-2803-4

Garcia-Granada A.A., Lacarac V.D., Smith D.J., Pavier M.J. A new procedure based on Sachs' boring for measuring non-axisymetric residual stresses: experimental application. International Journal of Mechanical Sciences 43 (2000) 2753-2768

Geng H., Xu X., Lai Z., Cao Q., Li L. A novel non-contacting single-coil electromagnetic hole expansion process to improve thefatigue performance of hole component. Int. J. Fatigue 162 (2022) 106924

Gu H., Jiao L., Yan P., Song Y., Guo Z., Qiu T., Wang X. Hole surface texture reconstructed with laser shock peening and effect on fretting behavior. Wear 494-495 (2022) 204242

Guo Z., Zengqiang C., Yangjie Z. A dynamic cold expansion method to improve fatigue performance of holed structures based on electromagnetic load. International Journal of Fatigue 148 (2021) 106253

Zheng G., Cao Z., Zuo Y. Fatigue life enhancement mechanism and lifetime prediction of AA6061-T6 open-holed sheet treated by electromagnetic driving dynamic cold expansion. Materials Today Communications 33 104841 (2022)

Hamuiela J., Kuznetsov Y.N., Hamuiela T.O. Genetic morphological synthesis of chucks. Lutsk, Veja-Druk (in Russian) (2017)

Hogenhout F. Method and apparatus for hole coldworking. USA Patent 4583388, Patented April 22 (1986)

Huang Y., Li H., Yang X., Guan Z., Li Z., Sunc Y. Improving the fatigue life of 2297-T87 aluminum-lithium alloy lugs by cold expansion, interference fitting, and their combination. Journal of Materials Processing Tech. 249 (2017) 67–77

Ivetic G., Meneghina I., Troiania E., Molinaria G., Ocanab J., Morales M., Porro J., Lanciotti A., Ristori V., Polese C., Plaisier J., Lausi A. Fatigue in laser shock peened open-hole thin aluminium specimens. Materials Science and Engineering A 534 (2012) 573– 579

Jae-Soon Jang, Dave Kim, Myoung-Rae Cho. TheEffect of Cold Expansion on the Fatigue Life of the Chamfered Holes. J. Eng. Mater. Technol.130(3): 031014 (2008) https://doi.org/10.1115/1.2931156

Jones K.W., Bush R.W. Investigation of residual stress relaxation in cold expanded holes by the slitting method. Engineering Fracture Mechanics 179 (2017) 213–224

Kennedy J.R., Larson D.J. Method of cold working holes using a shape memory alloy tool. USA Patent 5265456, Patented Nov. 30 (1993)

Kumar S.A., Badu N.C.M., Influence of Induced Residual Stresses on Fatigue Performance Cold Expanded Fastener Holes. 5th International Conference of Materials Processing and Characterization. Materials Today Proceedings 4 (2017) 2397-2402

Kuo A.S. Coldwork holes with reusable seampless SMA sleeve. USA Patent 6266991, Patented July 31 (2001)

Lancotti A., Polese C. The effect of interference-fit fasteners on the fatigue life of central hole specimens. Fatigue Fract Eng Mater Struct 28 (7) (2005) 587-597

Leon A. Benefits of split mandrel coldworking. Int. J. Fatigue 20 (1998) 1–8

Leon A. The Advanced Split Mandrel Coldworking Process in Various Military Life Extension Applications. The Advanced Split Mandrel Coldworking Process in Various Military Life Extension Applications. SAE Transactions 107 (1998a) 1393–1397 http://www.jstor.org/stable/44735870

Li Q., Xue Q., Hu Q., Song T., Wang Y., Li S. Cold Expansion Strengthening of 7050 Aluminum Alloy Hole: Structure, Residual Stress, and Fatigue Life. International Journal of Aerospace Engineering (2022) 4057898 https://doi.org/10.1155/2022/4057898

Liu F., Su H., Xu J., Liang Y. Fatigue performance on 7050 aluminum alloy by twice hole expansion strengthening of split mandrel. Int J Adv Manuf Technol 129 (2023) 2241–2256. https://doi.org/10.1007/s00170-023-12416-8

Liu H., Hu D., Wang R., Wang X., Jin S., Gu Y. Experimental and numerical investigation on the influence of cold expansion on low cycle fatigue life of bolt holes in aeroengine superalloy disk at elevated temperature. Int. J. Fatigue 132 (2020) doi.org/10.1016/j.ijfatigue .2019.105390.

Liu J., Xu H.L., Zhai H.B., Yue Z.F. Effect of detail design on fatigue performance of fastener hole. Mater. Des. 2010, 31 (2010) 976–980

Liu J., Yue Z.F., Liu Y.S. Surface finish of open holes on fatigue life. Theor. Appl. Fract. Mech. 47 (2007) 35–45

Liu K.Y., Zhou L., Yang X.S. Finite Element Simulation of the Cold Expansion Process with Split Sleeve in 7075 Aluminum Alloy. J. Inst. Eng. IndiaSer. C102(2) (2021) 1–1

Liu K., Yang X., Zhou L., Li M., Zhu W. Numerical investigation of the effect of hole reaming on fatigue life by cold expansion. Transactions of the Canadian Society for Mechanical Engineering 46 (2) (2022) https://doi.org/10.1139/tcsme-2021-0123

Liu F., Su H., Xu J. et al. Fatigue performance on 7050 aluminum alloy by twice hole expansion strengthening of split mandrel. Int J Adv Manuf Technol 129 (2023) 2241–2256 https://doi.org/10.1007/s00170-023-12416-8

Lv Y., Dong M., Zhang T., Wang C., Hou B., Li C. Finite Element Analysis of Split Sleeve Cold Expansion Process on Multiple Hole Aluminum Alloy. Materials 16 (2023) 1109

Maksimov Y.T., Duncheva G.V., Device and tool for cold expansion of fastener holes. Patent No: US 8,915,114 B2, Dec., 23.2014

Maximov J., Duncheva G., Anchev A., Dunchev V., Daskalova P. Modified Split Mandrel Method and Equipment to Improve theFatigue Performance of Structural Components with Fastener Holes. Metals 14 (2024) 303. https://doi.org/10.3390/met14030303

Maximov J.T., Duncheva G.V., Amudjev I.M. A novel method and tool which enhance the fatigue life of structural components with fastener holes. Eng Fail Anal 31 (2013) 132-143

Maximov J.T., Duncheva G.V., Anchev A.P. An approach to modeling time-depending creep and residual stress relaxation around cold worked hoels in aluminium alloys at room temperature. Eng Fail Anal 45 (2014) 1-14

Maximov J.T., Duncheva G.V., Ganev N. Enhancement of fatigue life of net section in fitted bolt connections. J Const Steel Res 74 (2012) 37-48

Maximov J.T., Duncheva G.V., Ganev N., Amudjev I.M. Modeling of Residual Stress Distribution around Fastener Holes in Thin Plates after Symmetric Cold Expansion. J Braz Soc Mech Sci Eng 36(2) (2014) 355-369

Maximov J.T., Duncheva G.V. A new 3D finite element model of the spherical mandrelling process. Finite Elements in Analysis and Design 44 (2008) 372– 382

Maximov J.T., Duncheva G.V. Device and Tool for Cold Expansion of Holes. International Application Published under the Patent Cooperation Treaty (PCT) WO 2014/012153 A1, 23 January 2014 (2024)

Maximov J.T., Duncheva G.V., Amudjev I.M. A novel method and tool which enhance the fatigue live of structural components with fastener holes. Engineering Failure Analysis 31 (2013) 132-143

Maximov J.T., Duncheva G.V., Amudjev I.M., Anchev A.P., Ganev N. A new approach for pre-stressing of rail-end-bolt holes. Proc. IMechE, Part C: J. Mechanical Engineering Science 231 (12) (2017) 2284-2290

Maximov J.T., Duncheva G.V., Anchev A.P., Amudjev I.M. New method and tool for increasing fatigue life of a large number of small fastener holes in 2024-T3 Al-alloy. J Braz Soc Mech Sci Eng 41 (2019) 203 DOI: 10.1007/s40430-019-1709-8

Maximov J.T., Duncheva G.V., Anchev A.P., Amudjev I.M., Kuzmanov V.T. Enhancement of fatigue life of rail-end-bolt holes by slide diamond burnishing. Eng Solid Mech 2 (2014a) 247-264

Maximov J.T., Duncheva G.V., Anchev A.P., Dunchev V.P. Crack resistance enhancement of joint bar holes by slide burnishing using new tool equipment. Int J Adv Manuf Techn 102 (9-12) (2019a) 3151-3164

Maximov J.T., Duncheva G.V., Anchev A.P., Ichkova M.D. Slide burnishing – review and prospects. Int J Adv Manuf Technol (2019b) DOI: 10.1007/s00170-019-03881-1

Maximov J.T., Duncheva G.V., Dunchev V.P., Anchev A.P. Slide burnishing versus deep rolling – a comparative analysis. Int J Adv Manuf Technol (2020) DOI: 10.1007/s00170-020-05950-2

Mishra R.S., Ma Z.Y., Charit I. Friction stir processing: a novel technique for fabrication of surface composite. Mater. Sci. Eng. A 341 (2003) 307–310

Ozdemir T. Experimental assessment of the redistribution of the 3D residual stresses during early fatigue at split-sleeve cold expanded reamed A/C fastener holes. Scientia Iranica 25(3) (2018) 1153-1168 doi:10.24200/sci.2017.4340

Philips A. Coining Structural Parts. U.S. Patent 3110086, 12 November (1963)

Philips A. Ring pad stress coined structure. USA Patent 3895922, Patented July 22 (1975)

Philips A. Ring pad stress coining. USA Patent 3796086. Patented Mar. 12 (1974)

Pucillo G.P., Carrabs A., Cuomo S., Elliott A., Meo M. Cold expansion of rail-end-bolt holes: Finite element predictions and experimental validation by DIC and strain gauges. International Journal of Fatigue 149 (2021) 106275

Quincey D.E., Copple C.M., Walsh W.B., Jarzebowicz R.Z., Easterbrook E.T. Split sleeve cold expansion. USA Patent 5305627, Patented Apr. 26 (1994)

Raza A., Kumar S. A critical review of tool design in burnishing process. Tribology International 174 107717 (2022)

Rodman G.A., Creager M. Split mandrel vs. split sleeve coldworking: Dual methods for extending the fatigue life of metalstructures. In Proceedings of the FAA/NASA International Symposium on Advanced Structural Integrity Methods for Airframe Durability and Damage Tolerance, Hampton, VA, USA, 4–6 May 1994; Harris, C.E., Ed.; NASA Conference Publication 3274 Part 2 (1994) 1077–1086

Shuai H., Youli Z., Zhihai C., Yanli W., Yongheng N., Xiaokun D. Effect of hole cold expansion on fatigue performance of corroded 7B04-T6aluminium alloy. International Journal of Fatigue 126 (2019) 210–220

Sikhamov R., Fomin F., Klusemann B., Kashaev N. The Influence of Laser Shock Peening on Fatigue Properties of AA2024-T3 Alloy with a Fastener Hole. Metals, 10 (2020) 495 doi: 10.3390/met10040495

Speakman E. "Fatigue Life Improvement Through Stress Coining Methods." Achievement of High Fatigue Resistance in Metals and Alloys. Ed. ASTM Committee E-9, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959: ASTM International (1970)

Split Mandrel Puller Tooling Manual OM-SM-9302-3; West Coast Industries: Seatle, WA, USA. Available online: https://coldwork.com/images/pdfs/SM_Tooling.pdf (accessed on 29 February 2024)

StressWave Inc. Final Report, FEBRUARY 2009 AFRL-RX-WP-TR-2009-4027

Stuart D.H., Hill M.R., Newman J.J. Correlation of one-dimensional fatigue crack growth at cold-expanded holes using linear fracture mechanics and superposition. Eng. Fract. Mech., 7 (2011) 1389–1406

Su R., Huang L., Xu C., He P., Wang X., Yang B., Wu D., Wang Q., Dong H., Ma H. Factors Influencing Residual Stresses in Cold Expansion and Their Effects on Fatigue Life—A Review. Coatings 13 (2023) 2037 https://doi.org/10.3390/coatings13122037

Tolga Bozdana A. On the mechanical surface enhancement techniques in aerospace industry – a review of technology. Aircraft Engineering and Aerospace Technology: An International Journal 77/4 (2005) 279–292 DOI 10.1108/00022660510606349

Trung-Thanh Nguyen, Xuan-Ba Le. Optimization of roller burnishing process using Kriging model to improve surface properties. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 233 (12) (2019) https://doi.org/10.1177/0954405419835295

Vallieres G.M., DuQuesnay D.L. Fatigue life of cold-expanded fastener holes with interference-fit fasteners at short edge margins. Fatigue Fract Eng Mater Struct (2014) https://doi.org/10.1111/ffe.12257

Wang C., Zou F., Zhou E., Fan Z., Ge E., An Q., Ming W., Chen M. Effect of split sleeve cold expansion on microstructure and fatigue performance of 7075-T6 aluminum alloy holes. Int. J. Fatigue 167 (2023) 107339

Wang X., Cao Z., Guo Y. Effect of interference installation method on interfacial properties and fatigue failure behavior of bolted composite joints. Journal of Composite Materials 58(13) (2024) 1537-1554 doi:10.1177/00219983241244565

Wang X., Xu C., Chen X., Hu D., Hu Bo., Hu R., Gu Y., Zhihui Tang. Effect of cold expansion on high-temperature low-cycle fatigue performance of the nickel-based superalloy hole structure. International Journal of Fatigue 151 (2021) 106377

Wang Y., Fu B., Nie L., Sun T. Fatigue nucleation site of cold expansion hole varying as fatigue load level varies. SN Applied Sciences 1 (2019) 867 https://doi.org/10.1007/s42452-019-0880-y

Wang Zhi-Yu, Wang Qing-Yuan, Cao Mengqin. Experimental Study on Fatigue Behaviour of Shot-Peened Open-Hole Steel Plates. Materials 10 (2017) 996 doi:10.3390/ma10090996

Yan W.Z., Wang X.S., Gao H.S., Yue Z.F. Effect of split sleeve cold expansion on cracking behaviors of titanium alloy TC4 holes. Eng Fract Mech 88 (2012) 79-89 dx.doi.org/10.1016/j.engfracmech2012.04.008.

Yan-li W., You-li Z., Shuai H., Han-xiao S., Yong Z. Investigation on fatigue performance of cold expansion holes of 6061-T6. International Journal of Fatigue 95 (2017) 216–228

Yuan X., Yue Z.F., Wen S.F., Numerical and Experimental Investigation of the Cold Expansion Process with Split Sleeve in Titanium Alloy TC4. Int. J. Fatigue 77 (2015) 78–85

Zhang Q., Zuo Y. Fatigue Behavior Investigation of Interference Fitted Pinned Joints with Extremely Small Edge Distance. J. of Mater Eng and Perform. (2023) https://doi.org/10.1007/s11665-023-08406-2

Zhang T., Du X., He Y., Ma B., Zhang Ti. Finite Element Simulation of Residual Stress around Split Sleeve Cold Expanded Hole for AA7075. Journal of Physics: Conference Series 2 (2020) 1624 doi:10.1088/1742-6596/1624/2/022041

Zheng G., Cao Z., Zhang M. A novel method to improve fatigue behaviors of holed structures based on electromagnetic force. Proc I Mech E Part C: J Mechanical Engineering Science 236 (11) (2022) 6170-6179 DOI: 10.1177/09544062211064129

Zheng G., Cao Z., Zuo Y., Zuo D., Ou P., Chen H. Residual stress distribution and fatigue performance investigations of electromagnetic force-based dynamic cold expansion open-holed sheet. Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications. 237(5) (2023) 1109-1123. doi: 10.1177/146442 07221136266

Zhou Z., Fu J., Cao Q., Lai Z., Xiong Q., Han X., Li L. Electromagnetic cold-expansion process for circular holes in aluminumalloy sheets. J. Mater. Process Technol. 248 (2017) 49–55