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INNOVATIVE METHODS, DEVICES AND TOOLS FOR ENHANCEMENT OF FATIGUE LIFE OF STRUCTURAL COMPONENTS WITH NATURAL CONCENTRATORS

Jordan Maximov* **Galya Duncheva**
Technical University of Gabrovo

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Abstract

The article presents the results of many years of work of the authors and their collaborators in the field of enhancement of fatigue life of steel structural members with natural stress concentrators through introduction and control of beneficial residual stresses around the stress concentrators. Innovative methods, devices and tools for pre-stressing of fastener holes, rail-end-bolt holes, external cylindrical surfaces have been developed and patented. They can be used in aircraft industry, railway transport and other.

Keywords: enhancement of fatigue life; stress concentrators; cold working; burnishing; fastener holes; shifts and axles

1. INTRODUCTION

The exploitation of the technical products is associated with transmission of a power flow between their components by a contact interaction on their working surfaces. Besides the working loading, the surface layers are subjected to different environmental influences: temperature and electro-magnetic fields, chemical active environment and others. At the same time the surface layers are carriers of various natural concentrators of deformations and stresses. The most common natural concentrators are the fastener holes designed for bolts and rivets. Consequence the effect of local concentration, the working stresses are larger in absolute value in the points from the hole surface. For instance, the working stresses around cylindrical holes in samples subjected to tension, are approximately three times higher than the nominal ones, which could arise in a specimen without a hole [1]. In the presence of static load, the crack resistant of the respective structural component is determined by the condition of the material around the hole. If the external load is dynamic or particularly cyclical, a process of initiation and growth of fatigue cracks occurs. After reaching a critical length of the fatigue crack, a fatigue failure of the corresponding structural component suddenly arises [2]. As a whole, most of metallic structural members are exposed to dynamic or cyclic load. Typical examples are the numerous structural components with fastener holes in the aircraft industry (Fig. 1), the automotive industry, numerous components in the ships and yachts, bolted rail joint (Fig. 2), as well as bridges (Fig. 3a) and crane facilities (Fig. 3b), offshore and others.

The material fatigue process is intensified in the greatest extent, when the maximum working stresses are tensile or shear. As a result, first-mode fatigue cracks are initiated, starting usually from the surface of the hole (Fig. 4), or on the front surfaces. The latter are the result of high contact stresses and small relative displacements – a phenomenon known as "fretting fatigue". This phenomenon occurs for instance in bolted joints loaded perpendicular to their axes with a pulsating load.

Therefore, the fatigue is a major factor determining the strength resource, lifetime and security of dynamic or cyclic loading metal parts with holes [3-7].

Fig. 1. Aircraft fatigue failure

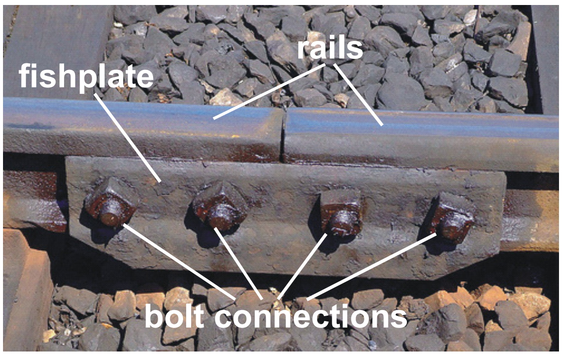

Fig. 2. Bolted rail joint component

* Тел.: 066827312; e-mail: maximov@tugab.bg

a.

b.

Fig. 3 Fatigue failure in metal structures
a). bridge structure; b). offshore structure

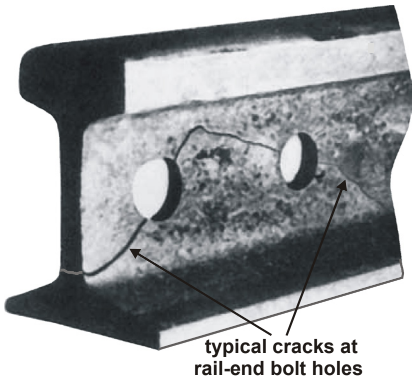

Fig. 4 Typical cracks originating at rail-end-bolt hole

Typical structural members, whose security and resource during an operation are limited by the state of the surface layers, are shafts and axles. On one hand, the external cylindrical surfaces are subjected to cyclically variable operating bending stresses with the largest amplitudes. On the other hand the shafts and axles interact with other components by contact interactions on their surface layers. Therefore, the life-time and the security during operation is limited by the fatigue life. Both processes - the fatigue and the wear, depend on the material state of a macro-, meso- and micro- level in the surface layers. This state is defined by a set of features, well-known as "surface integrity" (SI). SI is dependent on the process of preparation of a particular structural component, but in the greatest extent it depends on the type of finish treatment. The increase of the fatigue life and the wear resistance require an appropriate technology aimed at achieving the necessary set of quality characteristics of the surface layer: minimum roughness, increased microhardness, residual normal compressive stresses, maximum depth of the compressive field.

When the focus is on increasing the fatigue life, the distribution in qualitative and quantitative aspect of the residual stresses in the surface layers is essential. When the natural concentrators are fasteners or structural holes, the residual normal hoop compressive stresses act like a bracket, which "closes" the existing first-mode cracks and thus it prevents their growth and impede the formation of new ones. In the case of shafts and axles, the focus is on the residual axial normal stresses. Is well known that, as a whole, the processing by cutting introduces residual tensile stresses [8]. When the material of the structural components is a non-ferrous alloy, one of the most widely used for finish machining operations - grinding – is eliminated as a possibility. In this regard the technology for achieving a desired set of properties must be based on cold plastic deformation, having temperature lower than the recristalization temperature of the respective material. It is based on the idea of mechanically treating the surface layer with a tool, having hardness considerably greater than that of the workpiece being treated. From this perspective the methods, implementing the concept of cold plastic deformation can be applied to ferrous alloys with plastic behavior. It is compatible with both the mobility requirements of the application process (as is the case in aircraft industry) and the possibility of processing on conventional machine tools. Depending on the depth of the layer in which plastic deformation is formed, two main approaches are known to increase the fatigue life of structural elements with natural concentrators:

- Burnishing Through deforming elements, plastic deformation is formed at shallow depth commensurate with the height of the roughness (under 1 mm);
- Cold working Plastic deformation is formed in a substantial depth in the surface layers (up to a few mm). As a result, almost the entire volume of the element is deformed as outermost layers undergo only elastic deformation. After termination of the expansion, plastic deformed layers are subjected to compression as a result of the natural tendency of the elastically deformable layers to return to its original position. The manifestation of this mechanism is the basis for the generation of useful area with residual compressive stresses.

A quantitative measure of the depth of impact is a linear strain in a point from the surface of the hole (the shaft):

$$\varepsilon_{t,0} = \frac{i_n}{d_o} \times 100, \%, \qquad (1)$$

where $\varepsilon_{t,0}$ is degree of cold expansion (DCE), $i_n = \left| d_t - d_o \right|$ is the interference fit, which is defined by the difference between the diameter d_t of the tool working surface and the diameter d_o of the hole (shaft) being treated. Obviously, depending on the interference fit i_n, the corresponding process can take an intermediate position in terms of the conceptions "burnishing" and "cold working".

The methods, which implement the concept "burnishing", can be classified by different features. According to the type of friction between deforming elements and machined surface, there are two types of methods: 1). Deformation by means of rolls or spheres, where the friction is "friction of rotation"; 2). deformation under the condition of sliding friction.

Multinational company Ecoroll - a world leader in the burnishing technology, focuses on the effects of processing, classifying the nomenclature of their tools into three main groups:

● *Roller burnishing* The method implements deformation by means of rollers (well-known in our country), aiming to achieve a very low roughness (mirror burnishing), increased hardness and reduced friction and wear. The method is widely used for finishing of holes and outer cylindrical surfaces;

● *Deep rolling* External cylindrical and profile surfaces (such as turbine blades) are processed by means of hydrostatic sphere. The main objective is increased operational reliability and strength of fatigue, so that the focus is placed on imported residual compressive stress. The main objective is increased operational reliability and strength of fatigue, so that the focus is placed on imported residual compressive stresses. Given the beneficial effects of the generation of beneficial residual compressive stresses, the company Ecoroll presents this method as a combination of burnishing and cold working. Additional beneficial effect is the increased corrosion resistance, which reduces potential occurrence of stress corrosion crack. Unfortunately this method is not applicable for the processing of structural members with openings.

● *Combined skive-burnishing* This method is used for finishing of the holes in hydraulic and pneumatic cylinders. The emphasis is placed on achieving the mirror surface of the hole and high precision to minimize the friction losses and wear. One of the most common methods that implements burnishing in terms of sliding friction is slide diamond burnishing. As the name indicates, the deforming element is diamond, often synthetic (in the country with the most diamond deposits in the world - Russia, and natural diamonds are used). Through the diamond burnishing the effect is similar to that achieved with deep rolling, but in terms of the depth of the compressive zone with beneficial residual stresses - even surpasses it. Generally, the method is primarily used for the processing of outer cylindrical surfaces, wherein the pattern of the processing presupposes the use of a universal tool - preferably with an elastically fixed deforming element. World leaders are the companies Elliott, Cogsdill Tool Products Inc., JD Tools. Overall, the method is cheaper compared to roller burnishing and deep rolling [9], and an advantage of the deforming element (diamond) is very small coefficient of friction with the metal workpiece – according to Korzynski [9], this friction coefficient is 0.02-0.08.

The pre-stressing the fastener holes as a implementation of the concept "cold working" is applied on the hole surface or on the frontal surfaces of the structural members close to the holes. The impact on the surface of the hole is performed in the conditions of a direct contact or through an intermediary, wherein the tool with a larger diameter passes through the opening from end to end. The most known methods, carrying out this concept in terms of fastener holes are: Ball Cold Working (the tool is a sphere) or Mandrel Cold Working (the tool is a mandrel with cylindrical working part), carrying out the process in terms of a direct contact [10]; Split Sleeve Cold Expansion (cold expansion (CE) through longitudinal split sleeve – intermediary) [11]; Split Mandrel Cold Working [12]. Nowadays the last two methods are the most widely used in countries like USA, UK, Australia and others. In those countries in the aircraft industry and railway transport, standard practices are implemented, developed by the company Fatigue Technology Inc. and based on the method Split Sleeve Cold Expansion. The other world leader is the company West Coast Industry, which has developed a technology, based on the method Split Mandrel Cold Working. The name of the method comes from the longitudinally slit mandrel, allowing alteration of the diameter through an axial mobile pin, placed in a central hole of the mandrel. The term "cold expansion" was introduced by Fatigue Technology Inc. in view of the absence of a relative axial displacement of the mandrel with respect to the hole surface, due to the split sleeve intermediary.

In fact, the layers around the hole surface are deformed in radial and in the axial direction due to passing through the workpiece of significant axial power flow. Therefore, these methods require the use of a support, through which the axial flow power is closed. These methods (collectively called mandrel cold working methods) have the following disadvantages:

● Significant gradient of the generated residual stresses along the hole axis as a result from the passing through the workpiece significant axial power flow. For this reason sometimes on the entrance face, a field with tensile residual stresses is created [13]. The presence of such an area is a precondition for the initiation and growth of dangerous corner cracks around the holes;

● Because of the passing through the workpiece axial power flow and the one-sided access, the process is carried out by means of a support located around the aperture. Due to the plastic deformation, the effect of flowing of the material occurs, more pronounced on the exit side of the workpiece, also known as "surface upset" [13];

● The principal scheme of these methods corresponds to dimensional (fitted) process. Relatively narrow tolerance of the predrilled hole is necessary and the technological cycle involves a mandatory control of both predrilled and the final holes, and the tool [13].

The other major approach which implements the concept of "cold working", is based on the idea of creating a zone with residual compressive stresses by means of mechanical impact on the faces of the structural elements immediately surrounding circular or non-circular openings. Such methods are the patented methods ring coining [14], pad coining [15] and stress wave [1]. They are characterized by a common disadvantage - relatively shallow zones of residual compressive stresses imparted around the openings. From this point of view these methods are most effective for aluminium alloys. Considering the wide application of steel, obviously, another solution is necessary, in order to generate more intensive and deeper zone with compressive residual stresses.

As a counterpoint to mentioned shortcomings of existing methods and technical solutions to their implementation, the authors of the article have developed a number of innovative methods, devices and instruments to increase the fatigue life of structural elements with natural concentrators. The basis of the innovation are the following ideas:

● Control of the creation of the area with residual stresses in qualitative and quantitative respect;

● Possibility for wider tolerances of the predrilled holes and on this basis a reduction of the operations number in the developed processes for the processing of fastener holes;

● Application of the specific kinematics of the processing tool in order to implement the technical innovations in terms of conventional machine-building equipment and achieve lower roughness and useful residual stresses.

This article is a summary of the technical nature and the results from application of the created innovations.