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STRENGTHENING THE WORKING SURFACES OF GEARS THROUGH DYNAMIC BURNISHING

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Abstract:
Known solutions of devices for crush hardening do not ensure sufficient effectiveness of machining the teeth of a gear working surfaces. Due to the need to increase the load to working machines, and thus the degree of gear effort, while reducing their dimensions (i.e. downsizing), it is necessary to search for, test and implement new solutions for strengthening the gears. The proposed solution of the device, intended for jet burnishing the working surfaces of the gear teeth with an arch tooth line met the increased requirements regarding the effectiveness of strengthening. Effective cooling and lubrication of the processed surface and a significant increase in the dynamic burnishing force enable exceptionally favourable operational properties of gear wheels to be obtained using the discussed device. The opposite direction of the peripheral speed of the machined wheel in relation to the speed of the burnishing stream allows for obtaining the greater depth of surface deformation, generating higher compressive residual stresses in the surface layer. The parameters of the burnishing process with this device can be easily adjusted within wide limits, and the final effect depends on the selection of the diameter and type of the backshot material, its ejection speed, processing time and the number of processing passes.

Key words: cylindrical gear, dynamic burnishing, fatigue life, surface cold treatment

INTRODUCTION

Mechanical gears used in the mining and construction industries are usually designed to produce high torque at a relatively low rotational speed. Mechanical transmissions used in heavily loaded machines and vehicles are subject to high requirements regarding their operational properties, because they are exposed to variable cyclic loads and unfavourable parameters [1, 2]. High operational loads to the gear may lead to damage to the gears caused by abrasive and erosive wear, fatigue chipping of the surface layer of the working surfaces of the teeth (pitting), and sometimes the teeth seizing. A particularly critical damage is the breaking of gear teeth, which leads to failure and forced stoppage, and in many cases constitutes an additional threat to work safety, especially in the gears of vehicles and working machines. The vast majority of tooth fatigue fractures begin at their base, because this is where the greatest material stress occurs. Additionally, the machining scratches resulting from the use of typical methods of cutting gears is unfavourable. Machining scratches are the notches that begin development of tooth fatigue cracks [3, 4, 5, 6, 7]. This results in particularly high requirements regarding the short-term strength, fatigue life and stiffness of gear wheels.

Gears must be able to withstand high dynamic loads, which may occur as a result of sudden load peaks, impacts or shocks. Gear teeth must be resistant to surface fatigue, which can lead to wear and erosion. Due to cyclic loading, the gear material undergoes fatigue process. The gear manufacturing process should minimize the risk of microcracks that may gradually lead to failure. In addition, stiffness of the gear wheels is important for precise and stable torque transmission and preventing tooth deformation under heavy loads. Transmission gears must also have high plastic properties because, if damaged, they should not undergo brittle fractures that could lead to sudden, catastrophic failure.

Due to the possibility of obtaining better operating parameters, such as lower wear, lower noise, higher efficiency, greater durability and the ability to transmit large torques, the gears with an arch tooth line are used. Such gear wheels are used in the drive systems of many machines, e.g. in reducers of transporting means, motor vehicles, heavy machinery, in the raw material industry and others. Bevel and cylindrical gears with arcuate teeth have a number of advantages over the gears with straight teeth. Improved alignment and contact between the wheel teeth ensure even loads and increase the ability to transmit heavy loads. Distributing forces over a larger tooth surface reduces the risk of damage to working surfaces and increases their durability. When the teeth are properly aligned and come into contact with a larger surface area, the vibration and noise associated with gear operation is minimized, making them more effective in industrial applications.

Increasing the operational properties of gears, which are key to improving their strength, durability and work efficiency, is the subject of numerous studies [8, 9, 10, 11, 12]. The change in design [8], appropriate selection of material [9], manufacturing technology [10] and gear machining [11], extensive diagnostic systems for early detection of damage [12] as well as stands and methodologies for testing gear wheels [13, 14, 15, 16] increase the operational durability and safety of use as well as the gear reliability. Cold processing by burnishing the working surfaces of the teeth gives a significant improvement in the above-mentioned operational properties of the gear. The burnishing technological process increases abrasion resistance, ensures fit durability and the ability to transfer higher surface pressures, and improves fatigue strength. In the case of gears, this procedure improves resistance to fatigue cracks and eliminates the unfavourable impact of machining scratches at the teeth base [17,18,19]. Despite so many beneficial properties offered by cold processing by burnishing, it is still used to a small extent to strengthen the working surfaces of gear teeth.

MATERIALS AND METHOD

Improper condition of the top layer of the working surface of the gear teeth contributes to the accelerated formation of gear wheels damage, the types of which are described in the following chapter. The paper presents an example of using the jet stream burnishing the gears with arcuate teeth to improve the fatigue life and abrasion resistance of the working surfaces of the teeth, which allows to obtain favourable operational properties of the gear. Technological process of jet stream burnishing the teeth can be performed by a device, the concept of which is presented in this section. Parameters of the burnishing process with this device can be easily adjusted within wide limits, and the final effect depends on the selection of the diameter and type of the backshot material, its ejection speed, processing time and the number of processing passes.

MAIN DAMAGES TO THE GEAR WHEELS

Gear damage can take many different forms, and its classification is handled by international [20] and national standardization committees [21, 22]. In operational practice of the working machines, two basic groups of gear damage can be identified. The first group includes damage to the working surface of the teeth, such as:

a) wear (most often abrasive, corrosive and erosive),
b) seizure,
c) permanent deformation (plastic deformation caused by turning, impact),
d) spalling (flaking of the surface layer)
e) pitting (chipping).

The second group includes damage caused by tooth fracture, such as: a) temporary fracture – brittle or ductile, fracture as a result of plastic deformation, "cutting off" the tooth, b) fatigue fracture of the tooth – at the base or on the edge of the tooth. In addition, there are technological damages (grinding scratches, grinding cracks, hardening cracks), which can initiate the further development of damages [21]. When designing and selecting the gears, special attention is paid to the most important operational properties, such as fatigue strength and resistance to seizure, especially at higher rotational speeds or high sliding speeds [23].

For this reason, the next part of the section focuses exclusively on a fatigue damage. There are two basic types of fatigue damage: fatigue damage of the tooth flanks (spalling and pitting, shown schematically in Fig. 1) and fatigue fracture of a tooth or other part of the gear wheel.

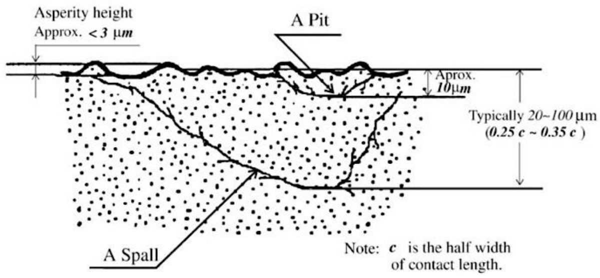
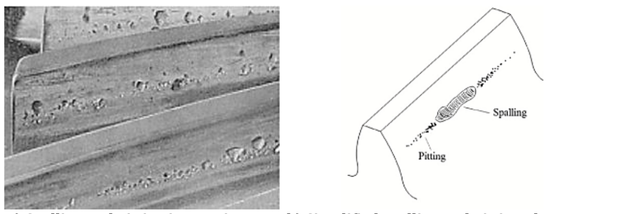


Fig. 1 Schematic illustration of spalling and pitting phenomena
Source: [24].

Although the physical nature of the fatigue process has not yet been fully explained, it is commonly accepted that the main cause of fatigue damage is inhomogeneity and structural defects of the material in the places of critical stresses of components subjected to cyclic loads [25]. Fatigue wear can take different forms (Fig. 2), depending on the conditions of movement of the components of the tribological system and the state of the contact stress.



a) Spalling and pitting in practice **b) Simplified spalling and pitting phenomenon**

Fig. 2 Gear tooth spalling and pitting
Source: [25, 26].

As a result of repeated contacts, microcracks are formed in the subsurface layer, which then emerge to the surface, leading to its defects. Spalling occurs in dry or not enough lubricated contacts during turning or rolling with a slip, most often on the surface of the teeth flanks of a hardened layer. This process consists in the separation of material in the form of scales. It is usually accompanied by oxidation of the material in the subsurface layer. Surfaces worn by spalling are characterized by large but shallow defects, irregularly distributed and covered with rolled particles separated from the surface layer [27]. Wear by pitting [28, 29] occurs in lubricated contacts during turning or rolling with slip, most often on the surface of the flanks of teeth of an unhardened layer (Fig. 3).

Fig. 3 Destructive (progressive) pitting
Source: [30].

Fatigue of the surface layer, caused by cyclic contact loads is the reason, but the wear mechanism is different from that in the case of spalling [25, 28]. Pitting most often appears at the tooth base area, where the highest pressures are caused by a small involute radius. The resulting craters merge into larger bands, contributing to a significant material losses with sharp edges. Pitting can lead to complete destruction of the tooth by breaking it off. Another type of fatigue damage is fatigue fracture of the tooth (Fig. 4), which is characterized by the presence of two separate zones on the fracture surface: the fatigue crack development zone and the immediate fracture zone. The fatigue crack most often appears in the area of the loaded side of the tooth, runs along its base or passes diagonally through its working surface [21].

Fig. 4 Fatigue crack
Source: [31].

Insufficient operational properties of gears in relation to loads to the working machines and vehicles in which they are used, cause fatigue cracks in the gears of mechanical transmissions. This is mainly due to incorrect strength calculations, overloads, material defects and damage caused by errors in the heat and mechanical treatment of gears [22].

OPERATING PROPERTIES AFTER STRENGTHENING BY BURNISHING THE SURFACE OF MACHINES AND EQUIPMENT COMPONENTS

Surface burnishing is a technological process used in metal processing, which involves plastic deformation of the material surface using devices of appropriate hardness and geometry. In this process, the workpieces are subjected to strong pressure, which causes changes in the structure of the material, especially on its surface. Burnishing is used to reduce surface roughness and to strengthen and harden the surface layer of the component [32].

Known methods of strengthening the surface layer [33] of machine components exposed to fatigue, abrasive wear and corrosion involve the use of static [34] or dynamic burnishing with mechanically loaded rollers or balls [35] or balls thrown by a stream of compressed air [36].

In industrial applications, the most frequently used strengthening method is a dynamic burnishing, which involves hitting the surface of the workpiece with a stream of steel or cast iron balls. High speed of the burnishing particles is achieved by compressed air or rotary mechanical ejectors [18, 37].

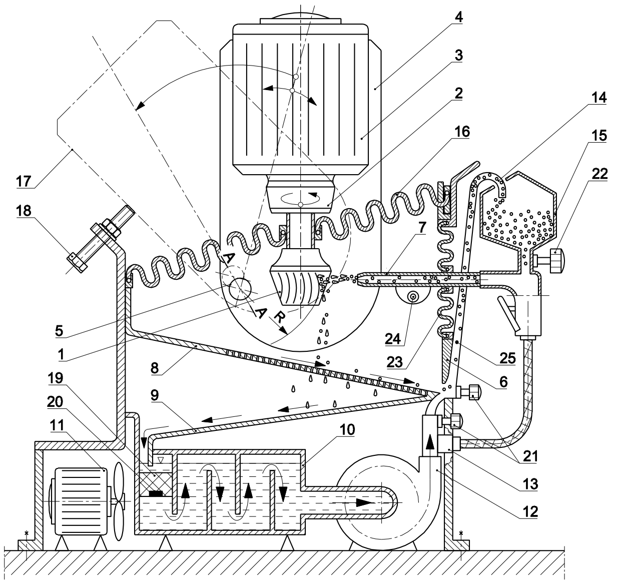
The kinetic energy of the striking balls causes changes in the geometric structure of the surface and in plastic and elastic deformations of the material of the surface layer of the workpiece. Such changes in the condition of the surface layer have a positive effect on its functional properties, in particular the increase in its fatigue strength [17, 37, 38]. The resulting micro deformations of the material surface increase its resistance to fatigue and cracking, improving its durability. Surface roughness also changes due to micro abrasion, the texture of which depends on the initial hardness of the workpiece and the kinetic energy of the striking balls. By selecting the appropriate conditions for the burnishing process, it is possible to obtain low roughness of the treated surface, which affects its load-bearing capacity, i.e. resistance to pressure.

Known devices for burnishing the machine components, such gear wheels, have been described in [17, 18, 19, 39, 40]. The methods and devices presented there have a number of physical limitations that make it impossible to get large strengthening effects. Treatment of the working surfaces of the wheels with higher hardness, made of alloy steels and subjected to hardening heat or thermo-chemical treatment, encounters serious limitations. For example, patent descriptions [41, 42] concern the devices in which a stream of small steel balls is accelerated to high speed and directed, using compressed air, to the treated surfaces. These devices have a limited air flow rate through jet nozzles, which makes it impossible to achieve greater burnishing depths. However, in the case of mechanical rotor ejectors, as the rotational speed of the ejectors increases, the abrasive wear of the backshot, rotors and nozzles increases significantly. Additionally, it favors formation of finely dispersed metal dust, which poses a risk of explosion. Moreover, all known devices for burnishing the machine components do not enable effective cooling of the burnishing zone, which causes a significant increase in the temperature of the burnished surfaces. This leads to unfavorable relaxation of residual stresses, shaped during burnishing, and to recrystallization of deformed material structures. All these factors further reduce the effectiveness of known devices used for burnishing the machine components. The test results presented in [37] indicate that the use of processing liquid in burnishing has a positive effect on the functional properties of the surface layer and the fatigue strength of burnished objects.

Known solutions of jet stream burnishing devices do not provide sufficient efficiency in machining the working surfaces of gear teeth. These devices do not allow limiting the temperature, which increases during processing as a result of converting the work of plastic deformation into heat, and therefore do not prevent the unfavourable relaxation of residual stresses. Due to the requirement of increasing the load to the working machines, and thus the degree of gear effort, while reducing their dimensions (so-called downsizing), it is necessary to search for, test and implement new solutions for burnishing the gear wheels. The increased requirements regarding the effectiveness of burnishing are met by the devices of the suggested design, intended for jet stream burnishing the gear teeth with an arcuate teeth.

DEVICES FOR STRENGTHENING BY BURNISHING THE WORKING SURFACES OF ARCUATE TEETH OF GEARS

The concept protected by patent [43], developed at the Silesian University of Technology, can be used to improve fatigue strength, stiffness, resistance to abrasive and erosive wear, while maintaining high plastic properties of tooth working surfaces, a device for surface treatment of gears with arch teeth. The device is shown in Figs. 5, 6 and 7. A vertical cross-section through the working chamber of the device is shown in Fig. 5. The position of the jet stream nozzle relative to the treated gear is shown in Fig. 6, and the eccentric system for adjusting the position of the central joint of the device (A-A) is presented in Fig. 7.



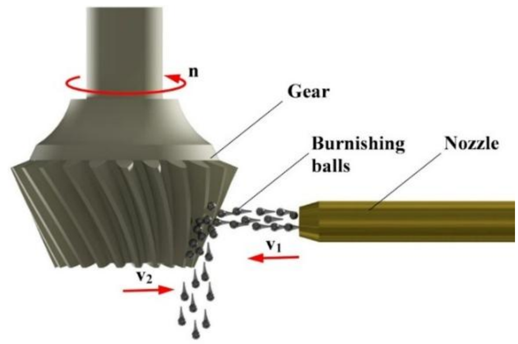
1 – gear, 2 – handle, 3 – drive motor, 4 – console, 5 – eccentric, 6 – enclosure of the working chamber, 7 – nozzle, 8 – grate, 9 – flow gutter, 10 – treatment liquid tank, 11 – fan, 12 – pump, 13 – distributor, 14 – pipe, 15 – reservoir, 16 – rubber cover, 17 – position of the console articulation, 18 – adjusting screw, 19 – filter, 20 – magnet, 21, 22 – valves, 23 – flexible cover, 24 – ball joint, 25 – burnishing balls

Fig. 5 Device for burnishing the working surfaces of gears with arcuate teeth

Source: [43].

The treated gear 1 (in this case the pinion of the bevel gear) is mounted in a self-centring holder 2, driven by an electric motor 3, which is mounted on an articulating console 4. The console is capable of swinging around the central joint, consisting of an eccentric 5, mounted in the enclosure of the working chamber 6. The rotating gear 1 is machined with a stream of balls with the cooling and lubricating machining fluid, ejected through the gun nozzle 7, suspended on the ball joint 24. A water-oil emulsion with addition of corrosion inhibitors can be used as a treating fluid, effectively removing the heat generated during the burnishing process.

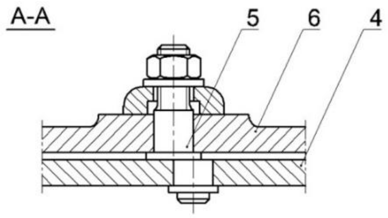
The stream of machining liquid with balls, after hitting the processed tooth surface, falls onto the perforated grate 8, where the balls are separated from the liquid. The machining fluid flows by gravity through a gutter 9, shaped like a funnel, into the tank 10, where it is cleaned and cooled with an air stream from the fan 11. At the entrance to the machining fluid tank, a filter 19 with a magnet 20 is installed, which captures metallic wear products. After cleaning and cooling, the liquid is sucked in by the pump 12, from where it goes under high pressure to the distributor 13. The liquid flowing out under pressure from the distributor feeds the gun nozzle 7 and transports the burnishing balls 25 through the pipe 14 to the tank 15. The balls wetted with the liquid are sucked in from the tank 15 through ejector-shaped flow system for nozzle 7, where the balls are imparted with kinetic energy by a high-pressure liquid stream. The stream of balls with liquid is directed to the working surfaces of the teeth of the processed gear 1 (Fig. 6) so that the direction of the speed vector v_1 of the ball stream is opposite to the direction of the peripheral speed vector v_2 of the gear 1.



n – rotational speed of the gear, v_1 – speed of the ball stream, v_2 – peripheral speed of the gear

Fig. 6 Position of the jet stream nozzle relative to the treated gear

During the machining, the console 4 reverses (swings) along with the drive motor and the treated gear 1. This movement enables obtaining the even machining along the entire arch length of the toothed gear 1. The treated wheel moves around the axis of the central joint, the centre of which corresponds to the centre of curvature of the tooth line, i.e. along the radius R (Fig. 5). Change in the radius R is realized by the eccentric 5 (Fig. 7). The swinging and reversing movement of console 4 can be performed by a computer-controlled stepper motor in accordance with the adopted program. After the teeth burnishing process is completed, the flexible rubber cover 16 is deflected, which causes the console to fully deflect to position 17, set by the adjusting screw 18. This allows the processed gear to be removed and the next one to be installed. In the case of machining the cylindrical wheels with an arcuate teeth, an additional pin should be used to fix the wheel in the holder 2. The gun nozzle 7 is suspended on the ball joint 24 and can be moved longitudinally thanks to the flexible cover 23. Valves 21 and 22 enable setting the optimal parameters of both machining streams.



4 – console, 5 – eccentric, 6 – enclosure of the working chamber
Fig. 7 Eccentric system for adjusting the position of the central joint of the device
Source: [43].

Use of the opposite sense of the peripheral speed of the treated wheel in relation to the speed of the burnishing stream allows for a significant increase in the kinetic energy of the collisions of the balls with the machined surface. The kinetic energy in the described situation is approximately proportional to the square of the sum of the above-mentioned speeds. This results in a large increase in the efficiency of jet stream burnishing, a greater depth of surface deformation and a higher degree of increase in the surface hardness of the treated teeth. In total, this contributes to an increase in the fatigue strength of the teeth, increased resistance to abrasive wear and improved contact strength (pitting resistance). This occurs as a result of the formation of a higher compressive stresses in the surface layer thanks to the use of the device according to the suggested solution.

For jet stream burnishing of the working surfaces of gear teeth, the hardened steel balls (e.g. bearing balls) or sintered carbide balls can be used, which, thanks to their higher density, increase the kinetic energy of the burnishing jet stream.

The use of a cooling and lubricating processing fluid provides very effective cooling of the treated zone, which protects against an undesirable increase in temperature, leading to the recrystallization of plastically deformed structures of the wheel material and the relaxation of the internal stresses formed in the jet stream burnishing process. The additional lubricating effect of the processing fluid reduces the abrasive wear of the components of the system, especially the balls, and wetting the dust generated during processing protects against its explosion and facilitates the removal of wear products from the working zone of the device.

The jet stream burnishing device according to the solution allows for a wide range of adjustment of burnishing parameters, such as the rotational speed of the processed wheels, the pressure of the processing fluid, the type of material and the size of the balls in a stream, the distance of the gun nozzle outlet from the processed surfaces, the processing time and the number of processing passes. The selection of the most favourable processing parameters depends on the type of material and the size of the gears, the type of processing, the purpose of the gear and the planned final effects.

The device according to the solution can be used at the final stage of gear wheel manufacture and during regeneration procedures during the gears repair. It can be easily adapted for processing by jet burnishing of gear teeth with a different longitudinal tooth line.

Use of the device according to the solution allows for achieving great technical and economic effects in the drive technology of machines and vehicles, with relatively low energy consumption.

SUMMARY AND CONCLUSIONS

The device for strengthening the gears by jet stream burnishing is designed for the final processing of gears to give them higher resistance to fatigue fracture of the teeth and is especially recommended for the processing of gears with an arcuate teeth.

As a result of burnishing the working surfaces of the gears, compressive stresses are formed in the burnished layer, which significantly increases the resistance to fatigue cracking. Additionally, jet burnishing leads to the neutralization of inevitable surface defects of the gears, such as machining scratches, non-metallic surface inclusions or gas bubbles. In addition, burnishing of the surface increases the resistance to the nucleation of fatigue cracks, eliminating micro-irregularities created during machining.

Use of the opposite sense of the peripheral speed of the treated gear in relation to the speed of the burnishing jet in the proposed solution of the device allows for a significant increase in the kinetic energy of collisions of the balls with the treated surface, which allows for obtaining exceptionally advantageous functional properties of the gears. Increasing the energy of jet burnishing allows for a greater depth of surface deformation and for the generation of higher compressive residual stresses in the surface layer.

The device is equipped with at least one nozzle spraying the cooling and lubricating processing fluid, which ensures effective cooling of the treated zone. This prevents against undesirable increase in temperature, which could lead to recrystallization of plastically deformed material structures and relaxation of residual stresses generated in the jet stream burnishing process. The lubricating effect of the processing fluid increases the smoothness of the machined surface, eliminating undesirable machining scratches and reduces abrasive wear of the system components. Wetting the dust generated during processing protects against the risk of explosion and facilitates removal of wear products from the working area of the device.

Parameters of the jet burnishing process can be easily adjusted within wide limits, and the final effect of processing depends on the selection of the backshot diameter and type of the material, its ejection speed, processing time and the number of processing passes. The favourable

processing parameters should be selected experimentally, due to the large number of gear wheel sizes, their modules, types of materials, tooth processing methods and heat and thermochemical treatment parameters.
The device for industrial use in strengthening the working surfaces of teeth by jet burnishing can be used both at the stage of gear wheel manufacture and repeated after a certain period of their operation to fully or partially restore the lost performance properties.

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