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IMPROVEMENT OF THREADED JOINT RELIABILITY BY MEANS OF ELECTROMECHANICAL PROCESSING

Liliya V. FEDOROVA[1], **Yulia S. IVANOVA**[1], **Marianna V. VORONINA**[2]
[1] *Bauman Moscow State Technical University, Moscow, Russia*
[2] *Saint-Petersburg Mining University, Saint-Petersburg, Russia*

The paper presents technological schemes of electromechanical processing (EMP) and examines formation specifics of high strength steel structures in the area of thermomechanical highly-concentrated strain on the root and flanks of external and internal threads. Testing results of EMP implementation are described. Materials of this paper are of practical value to specialists in various fields, related to the issues of improving threaded joint reliability.

Key words: wear resistance, thread, surface layer, electromechanical processing, microhardness, fatigue strength, drill pipe threads, tubing threads

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Introduction. Improvement of thread quality in drill pipes, subs and adaptors, tubing and casing, housing of electric submersible pumps, and a wide range of hardware items is a highly relevant task. Low thread quality of the above mentioned parts is associated with construction specifics, technological difficulties of their production and reclamation, loading pattern and operational conditions.

The main method to define geometry of external and internal threads for parts of oil & gas and mining equipment is thread cutting. It is usually carried out using chasing tools or carbide inserts with full or partial profile. Methods of thread cutting with special chasers, especially on CNC machines, have gained wide acceptance. After geometric cutting, external and internal threads are checked with a go/no-go gauge; provided that the standard requirements are met, they assure reliability of the threaded connection. Production of new parts and reclamation of worn-out ones normally do not involve any problems with delivering required level of threading precision.

In order to improve reliability of threaded joints the following requirements have to be satisfied: high wear resistance, strength and fatigue durability of the thread; combination of a hardened surface and a soft ductile core of the material; optimal height and shape of surface microroughness; favourable (rounded) root shape; optimal orientation of metal fibres; residual clamping stress in the root area; protection from corrosion and hydrogen embrittlement; maintainability and preservation of the workpiece.

Existing methods of strengthening and improving functionality of steel threading are associated with the application of surface plastic deformation (SPD), thermal, thermochemical, laser, magnetic-pulse, thermomechanical and combined approaches to reliability enhancement.

Application of SPD methods (roller burnishing, shot blasting, ultrasonic machining) allows to increase fatigue durability of threaded parts. Despite creating optimal roughness, hardening the surface, forming the texture of metal fibres and residual clamping stress in the root area, SPD methods do not lead to any significant increase in wear resistance and strength of the thread.

The most widely used thermal method of increasing durability and strength of the material is its bulk hardening and subsequent high tempering. Tempering is usually applied to workpieces from medium-carbon structural steels (types 40X, 45, 45HGMA) with HRC values up to 28-36, and followed by threading. One has to admit that such hardening of the workpiece solves the problem of its overall strength, but not that of a thread. Besides, hardness in the interval of

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28-36 HRC does not guarantee high wear resistance of the thread in case of abrasive erosion and great bearing pressures. Insufficient thread strength (especially in the nipple) and its low durability pose major difficulties in the process of screwing together, e.g., the nipple and the coupling of the drill pipe. Processes of bulk thermal treatment are labour and energy intensive, have limitations related to workpiece sizes and decrease fatigue strength of the parts with stress raisers (threads, fillets etc.).

Among methods of thermochemical treatment (TCT), the most widely used ones are nitriding and carbonitriding. However, these TCT methods are difficult to implement, require adherence to elaborate production practices, are limited in size of processed parts, and cannot be used for threaded part reclamation [4].

Competitive industrial production provides a possibility to improve reliability of the machinery across the entire value chain, from work preparation to production, equipment operation and maintenance. A no less important issue is economic efficiency of the described methods.

The most promising way to reduce production costs and to improve equipment quality is processing of the workpiece surface with concentrated energy flows (CEF). Various methods of CEF processing share a number of common features: significant heat exposure of selected surface areas; quick heating of the material to the temperature of phase transition and even higher; plastic deformation of the heated material; rapid cooling by means of removing heat with an underlying workpiece layer. One of such methods is electromechanical processing (EMP) of threaded parts.

EMP technology incorporates the following approaches [1, 10]: electromechanical surface quenching [2, 11], electromechanical finishing and strengthening [3], electromechanical calibration, strengthening electromechanical reclamation. They all use innovative equipment and tools to perform surface quenching, finishing, strengthening and reclamation with concentrated electricity currents of commercial frequency (50 Hz).

Local heating of the workpiece surface under electrical current is characterized by maximal thermal efficiency EMP does not require extended furnace heating and has no limitations related to the size of process parts. The workpiece is not subject to deformation, and its surface has an optimal roughness. An important benefit of EMP is a possibility to process complex surfaces: threads, grooves, holes and parts with complex geometry.

Another competitive advantage of EMP technology is a possibility to exert flexible control over parameters of fast resistance heating and simultaneous hot plastic deformation of the surface material in order to form unique fast-quenched structures, alter micro-geometry of the surface and reduce grain size. It is the surface under most stress that defines material resistance to fatigue failure, contact endurance and other critical operational properties.

In the process of electromechanical surface quenching (EMSQ) the workpiece, which is fixed with a three-jaw self-centering chuck of the lathe, starts rotating. The roller presses to its surface with a fixed force, revolves around its axis and receives the feed motion. In the contact zone between the roller and the process surface the workpiece heats up to the temperature of 900-1100 °C and rapidly cools down due to subsurface layer. The size of the heating area depends on technological aspects of processing: pressing force of the instrument, shape and size of the roller, feeding, hardness of the process material, processing modes [9].

In the process of EMSQ, the greatest impact on the structure and therefore on the properties of the surface comes from the temperature in the contact area, which results from conversion of electricity into thermal energy.

Electromechanical finishing and strengthening (EMFS) solves the problem of creating a single technological complex of operations, encompassing mechanical, thermal, finishing and strengthening treatment of the treads on general-purpose and specialized machines.

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Fig.1. General view of the testing equipment (*a*) and experiment configuration (*b*)

Electromechanical finishing, strengthening and calibration (EMFSC), apart from EMFS effects, results in correction of geometric parameters of the thread, according to standards performed with a carbide tool under frictional sliding conditions.

Strengthening electromechanical reclamation (SEMR) reproduces geometric parameters of the thread, provides surface quenching, forms optimal roughness and texture of metal fibres at the thread root and adjacent flanks by means of ductile thermomechanical redistribution of the material [9].

Methods and research results. Fatigue life tests of threaded joints after EMFS treatment were carried out in the laboratory of strength properties in KamAZ technical research centre (Naberezhnye Chelny, Republic of Tatastan). The testing was carried out on a certified universal machine ZUZ-200, INOVA production (Fig.1). Research on geometric parameters of the thread and surface roughness of test parts was performed with the following equipment and tools: universal measuring microscope UIM-23 №770003; roughness measuring instrument Surcom-480A-14 №99930264; micrometer MBM №83865; caliper №430905. Hardness measurements were performed in the laboratory of metal technologies, using Rockwell method (national standard GOST 9013-59) under the load of 1.5 kN on the testing machine TR 5006; using Vickers method (national standard GOST R ISO 6507-1-2007) under the load of 0.5 N on the testing machine Durimet.

Examinations were performed on studs from low-carbon steel 20G2R (specification TU 14-1-5490-2000) of the standard size M16×1.5, BelZAN production, with the following chemical composition:

Chemical elements	C	Mn	Cr	Si	S	Ni	B	P	Mo	Al
Content in the steel, %	0.23	1.26	0.25	0.12	0.021	0.04	0.004	0.011	0.002	0.028

Two types of studs were compared in the tests: with a thread after rolling on one side; with a thread after EMFS treatment on the other side of the workpiece (Fig.2).

Microstructure examination was performed on longitudinal microsections, cut through workpiece threading. Initial microstructure of the blank parts was identical – ferrite-carbide mixture, secondary sorbite. Hardness in the workpiece core, at a half-radius distance in the section, one diameter apart from the thread face, amounted to 32-34 HRC.

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a *b*



Fig.2. Fragment of a stud with the threading (*a*) and a workpiece after EMFS treatment (*b*)

Fig.3. Fragment of the root microstructure after EMP

In the external metric thread, the greatest concentration of stress occured at the root. As EMFS technology is characterized by simultaneous influence of thermal factor and physical stress, it results in a surface structure of the thread root with extended metal fibres, quenched to the depth below the zone of surface plastic deformation. Examinations of the thread root after EMFS treatment demonstrated that its structure was heterogeneous (Fig.3). On the surface, the structure was finely divided, with grain sizes unidentifiable for optic microscopes. Below this structure metal fibres extended along the root and flanks, and below that metal structure demonstrated distinct phase transitions with no traces of plastic deformation. Transition zone was located at a relatively shallow depth and characterized by interchanging layers of quenched and initial metal structures. Such structure of the surface layer allows to improve thread quality while maintaining its geometric parameters. Other existing methods cannot guarantee such properties of the threading.

Contamination of the metal with non-metallic tramp elements was evaluated according to national standard GOST 1778-70; for oxides it corresponded to point impurities, for sulphides – to 1a level contamination.

Metallographic tests revealed that EMFS treatment of the threading allows to eliminate technological stress concentrators, create favourable texture of metal fibres with phase modifications of finely divided surface structure, excludes oxidation and decarbonization of the surface. It has been detected that microhardness of the surface threading, made from 20G2R steel, reaches the level of 48-52 HRC, with the strengthening depth up to 0.35 mm, while initial structure and properties of underlying layers remain unchanged (Fig.4). Metal fibres stretch along the bottom profile at the depth of 0.01-0.04 mm.

In fatigue life tests, studs were subject to cyclic strain by a harmonic force with the following parameters: $F_{min} = 1.5$ kN, $F_{max} = 32.4$ kN (stress ratio 0.05). Tests continued until the fasteners failed. The stud with rolled threading was 38 mm long. Length of experimental section with die threading, exposed to EMP, was 20 mm, height of the test nut – 12.5 mm. In case of premature failure of the rolled threaded area, it permitted to screw the nut on the remaining part and continue testing until the failure of the test area.

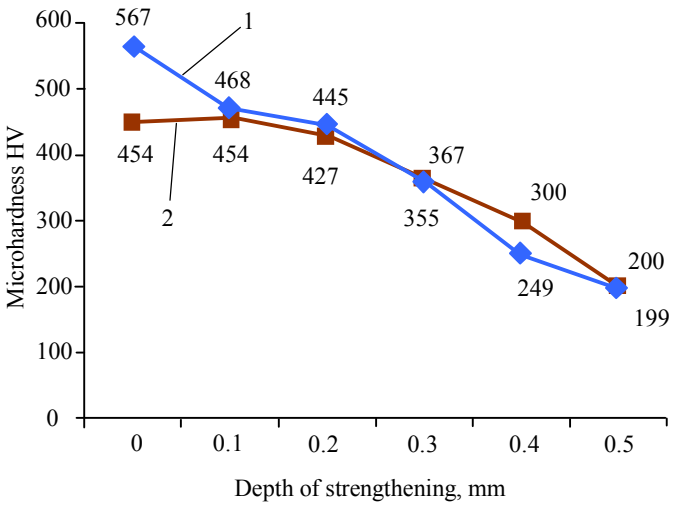


Fig. 4. Relation between microhardness and depth of strengthening at the thread flanks after EMP

1 – right side; 2 – left side

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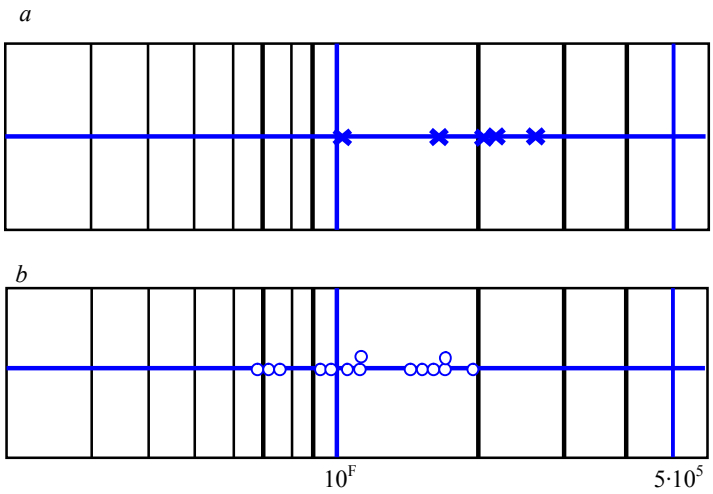


Fig.5. Results of fatigue tests:
a – die-cut threading, exposed to EMFS with cemented carbide VK6;
b – BelZAN studs

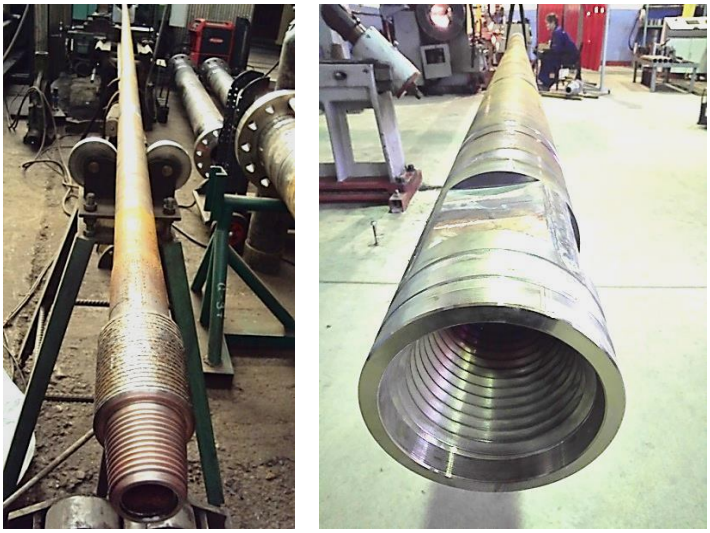




Fig. 6. Fragment of the workpiece threading after EMP

Comparison tests between die-cut studs with subsequent EMFS treatment of the thread root and samples with rolled threading without additional strengthening demonstrated that in the former case results are more stable and have lower variance. Average number of cycles before failure amounted to 141,600 for initial threading; 177,600 for threading after EMFS treatment. All the tested studs cracked in the first inactive turn under the nut. For illustration purposes pre-failure results for sample tests are presented on a logarithmic scale (Fig.5).

Hence, EMSF treatment of the thread root in steel studs increases fatigue life of thread joints by 25% and assures their stability compared to rolled threading. Results of operational tests have confirmed efficiency of electromechanical processing.

Several configurations of multifunctional power equipment and devices, implementing contact interaction between the tool and process surface of the workpiece, have already been designed and put into production [7, 8, 12, 13]. Recommendations have been developed on better ways to choose production accessories taking into account EMP type, durability of the electrode tool, and technological modes of processing, which depend on key characteristics of the strengthened surface layer, e.g. for parts of oil-field equipment (Fig.6).

Electromechanical processing of the thread gives the helical surface a set of unique properties, which are either very hard or altogether impossible to obtain with other methods [5, 6], in particular:

– a possibility to correct geometry of the cut thread with an instrument satisfying all technical standards;
– formation of the thread with a quenched surface and ductile underlying layers;
– absence of surface decarbonization and oxidation;
– favourable shape and configuration of metal fibres along the problematic section of the thread root;
– optimal shape and height of microroughness;
– surface hardness up to 5670 MPa, preservation of a soft core with the hardness of 1990 MPa;
– absence of oxidation, decarbonization and buckling of the parts;
– metal fibres extend along the threading profile;

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– depth of the deformed layer is 0.02-0.08 mm, whereas depth of the strengthened one is 0.04-0.35 mm;

– microgeometry of the surface decreases in height, its crests and rounded micro-valleys are flattened.

Results of applying EMP allow to come to the following conclusions:

– electromechancal finishing and strengthening of external and internal threads has the maximum depth of 0.35 mm; it increases microhardness of the material to the factor of 4 and at the same time improves its roughness (processing of the nipple thread on the tubing – oil and gas production departments NKT 60, 73, 89 «Yamashneft», TATNEFT);

– for threads on workpieces, subject to plastic deformations, EMFS treatment of the flanks should be performed at HV of 6000-8000 MPa, strengthening depth of 0.04-0.2 mm, with preservation of the soft core, and surface roughness of Ra 1.25-0.63 μm;

– for workpieces, subject to fatigue failures, the thread root should be given an optimal shape, with extended metal texture and favourable microgeometry.

Conclusions. Performed tests have defined new ways of improving thread quality in the areas of energy and resource saving, durability and reliability of equipment, reduction of labour required to produce and repair workpieces, improvement of companies' efficiency, environmental protection and manufacturing of compatible products.

These solutions may be beneficial for companies working in general-purpose and specialized mechanical engineering, construction of machines for oil extraction and refining, for mining and processing plants, Russian railways, transport and road-building companies, housing and utility services, water utilities, subways, confectionery production, power companies etc.

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Authors: **Liliya V. Fedorova,** *Doctor of Engineering Sciences*, *Professor*, *momd@yandex.ru* (*Bauman Moscow State Technical University*, *Moscow*, *Russia*), **Yulia S. Ivanova**, *Candidate of Engineering Sciences*, *Associate Professor*, *momd@yandex.ru* (*Bauman Moscow State Technical University*, *Moscow*, *Russia*), **Marianna V. Voronina**, *Candidate of Engineering Sciences*, *Associate Professor*, *maria.vv@mail.ru* (*Saint-Petersburg Mining University*, *Saint-Petersburg*, *Russia*).

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