Improving wear resistance of drill pipe sub thread by using final electromechanical surface hardening

S Fedorov¹², V Zaripov¹, Y Ivanova¹ and A Yakovleva¹
¹Bauman Moscow State Technical University, 5 Second Baumanskaia Street, Moscow, 105005, Russian Federation
²E-mail: momd@yandex.ru

Abstract. Improving wear resistance of drill pipe sub thread is a vital task, and finding effective solution for it would much assist oil and gas companies to enhance well construction process. The report presents the results of comparative wear resistance tests for P147/147 and P133/133 subs of the top drive manufactured by ООО «NIGMASH» in Bashkortostan. The tests were performed by ООО «Tatburneft» holding company, a division of PAO «TATNEFT». Both, series and test subs were made from 40Х2Н4А steel. This report shows the results of metallographic studies and tests for improvement of the parts wear resistance, including the method of final electromechanical hardening (EMH) of the box and pin threads as compared with the conventional method of bulk heat treatment. The researches has developed the equipment, tools and technology for hardening of tool joint thread of drill pipe subs. The performed tests and studies aimed at enhancing efficiency of oil and gas well drilling. Their results are of much interest for oilfield operators, drilling and service contractors, as well as drilling subs manufacturers and repair companies.

Introduction
Drilling of oil and gas wells is a time- and cost-consuming process, and application of new technologies helps in making this process more efficient. Typical drill string includes such elements, as drill bit, kelly, steel drill pipe and lightweight aluminum drill pipe with steel tool joints, subs, crossovers, centralizers, various design stabilizers and reamers, and drill collars. All the elements are made of high-quality alloy steel at specialized metallurgical plants and machine works. Russian oilfield drilling, service and production sector currently imports in large quantities a wide range of oilfield tools from world leading manufacturers from China, United States, Canada and Germany.

Drill string elements are connected with one another using thread connections. The most widely used is the tool joint thread connections with thread pitches of 5.08mm and 6.35mm. External (pin end) and internal (box end) threads are made using special CNC machines with special threading carbide plates or thread chasers. Thread is cut on steel billets with the hardness of 30–36 HRC after bulk heat treatment.

Drilling subs are used to connect drill string elements of different diameter or with different type threads, as well as to connect various fishing and auxiliary tools to drill pipe.

The lower sub (lower kelly cock) connects kelly with the upper drill pipe in the drill string, and the upper sub (upper kelly cock) connects kelly with the rotating swivel stem. Improving wear resistance of drill pipe sub thread is a vital task, and finding effective solution for it would much assist oil and gas companies to enhance well construction process. The most typical defects encountered on subs...
include OD wear and damage of internal and external threads. These defects frequently result in the forced interruption of the hole making process and rig downtime which lead to substantial economic losses.

The problem with damaged threads can only be resolved by increasing thread surface hardness [1] while maintaining high physical and mechanical properties inside the thread. The currently used technology of bulk heat treatment of billets and the following thread cutting does not ensure the required wear resistance of a thread surface. Instead of the planned 600 make-up and break-out cycles for drilling subs, 400 to 500 cycles is achieved at best. The required physical and mechanical properties of subs connection threads can be achieved by using combined methods of thread surface treatment involving concentrated energy streams (flows). These methods include such as thermochemical treatment (nitrogen hardening and carbonitriding), thermomechanical treatment, high induction hardening and laser hardening.

During high induction hardening (HIH) of medium-carbon structural steel the heat-up temperature rises to 930–950 °C. Also, heating up, heat exposure and colling down are applied in sequence while the billet is moved along the induction unit. Spray water colling is used for colling down the surface layer heated up by eddy-current. Using the HIH hardening method for tool joint tapered thread is highly problematic from the technological point of view. Furthermore, this method does not ensure the required hardening depth or the optimum physical and mechanical properties of the thread surface.

During the laser surface hardening the temperature in the treatment zone gets as high as 1000 °C—1100 °C and higher. Laser surface hardening is a non-contact hardening method featuring certain specific processes [2]. Laser surface hardening method ensures high level of the surface layer hardness, which negatively affect performance characteristics of threads of the drill string elements subjected to alternate and bending loads. Laser surface hardening of thread multiplies the risk of fatigue failure of a thread root.

Nitrogen hardening and carbonitriding are both efficient methods of hardening the drill string elements with a connection thread. Yet, the methods can only be applied in certain specialized conditions and require high standard production practices. Hence, cost of subs production significantly increases. Nitrogen hardening and carbonitriding increases hardness of not only connection threads, but also the outside diameter of subs. This causes such negative effects as wear of tong dies, galling of the sub OD, and problematic breaking out of drill pipe.

Among the methods of machines and tools surface hardening which uses the concentrated energy streams [3–5] electromechanical surface hardening technique is highly efficient[6, 7]. Theoretical studies and practical research for electromechanical hardening of connection threads [8–20] resulted in development of the electromechanical surface hardening method that can be used for improving service life of drilling subs connection threads.

The studies aimed at improving performance characteristics and extending service life of drilling subs by research, development and implementation of the final electromechanical hardening (ESH) of external and internal connection threads.

The following studies had to be performed to achieve the set objective:

1. Identify the main reasons for low service life of drill string subs and the criteria for their rejection.
2. Run comprehensive analysis of the existing methods and techniques of drilling subs external and internal connection thread surface hardening, and determine their interrelation with the operating requirements.
3. Carry out test work to support and confirm the applicability of electromechanical surface hardening technique for hardening of pin and box threads of drill string subs manufactured using pipe threading machines.
4. Run study and research to determine the effect of the thermomechanical interaction of the contact roller on alteration of geometrical and accuracy characteristics, structure and mechanical properties of the connection thread surface layer.
5. Run bench and field tests of the subs after pin and box connection threads electromechanical surface hardening.
6. Develop engineering and design documentation for the equipment, tools, accessories and process technique for electromechanical surface hardening of drill string subs external and internal connection threads.

7. Use the developed equipment and technology in subs production to harden connection threads. Run technical and economical assessment of the results.

**Experimental Result**

While being used in actual well drilling the subs connection threads is subjected to wear, as well as bending and torsional stresses. Uncontrolled reversal loads applied during making up and breaking out of thread connections cause such change of thread geometry as thread galling (Fig.1). For the best result to be achieved thread must feature high hardness while also maintaining sufficient modulus of resilience inside thread (Fig.2). Thread root must have a proper thread bottom shape and metal fibers should be located along the section of weakness. Thread flanks and bottom should have optimum height and microgeometry shape.

![Fig. 1. Wear of the element connection thread in the form of turns of thread galling](image1)

![Fig. 2. Performance requirements for drill pipe sub thread](image2)

When selecting the method of the drill sting subs connection threads surface hardening the following advantages of the EMSH technique should be taken into account:
- zero decarbonisation and oxidation of the surface due to the fact that the thermomechanical cycle of "heating up — heat exposure — deformation — cooling down" takes place only in the contact zone and lasts two decimal places of a second;
- ability to harden limited areas without thermomechanical effect on other surfaces of a drill string sub;
- individual approach towards each specific surface with account to loading pattern and operational conditions;
- ability to surface harden hollow and long elements and their individual surfaces without altering geometrical parameters of the hardened surfaces and with minimum thermal action level;
- the hardened surfaces feature high quality, homogeneity of the structure and uniformity of mechanical characteristics along the section and length of the surface;
- using the developed equipment and improving the tools for EMSH would allow to produce products of various configuration and dimension type;
- ecological cleanliness and electrical safety of the processes.

When EMSH method is used, the factor that most affects formation of the structure and, consequentially, the surface layer properties — is the temperature in the "tool - surface" contact zone generated by electric current. At optimum surface hardening mode, as a result of electric power transformation into heat energy, the contact zone instantly heated up to 1000 °C – 1100 °C. Heat removal from the high temperature zone goes through the below metal layers of the sub billet. Emulsion or water solutions with corrosion inhibitors cooling is used to preserve heat balance and prevent thread distortion.
For EMSH the sub is set in the chuck of a thread cutting machine and is rotated by rotational force $D_r$. The roller assembly is pushed at a certain fixed force to the sub surface, rotated about its axis and is imparted with a feed movement $D_s$. The contact zone between the roller and the surface been hardened the sub is been heated up to 1000…1100 °C and the surface layer cooled down fast. Cooling rate of the heated up surface layer reaches 2600 °C/sec, which is much faster than oil or water quenching. The dimensions of the heated up surface zone depend on such surface hardening technology factors as roller pressing force to the sub, roller shape and dimensions, roller feed rate, hardening material hardness, surface hardening mode, thermal conductivity of a drill pipe sub material, and heat transfer of the roller assembly.

Upgraded for electromechanical hardening 1M63 machine lathe of Alexandrovsky Drilling Equipment Plant was used to apply EMSH technique for hardening of drill string subs pin and box connection threads.

![Fig. 3. Schematic diagram of the electromechanical surface hardening of drill pipe sub pin connection thread](image)

![Fig. 4. Electromechanical surface hardening of drill pipe sub pin connection thread](image)

![Fig. 5. Final electromechanical surface hardening of the drill pipe sub box thread](image)

Same as when using other methods of intensive heating up, during EMSH the drilling sub surface layer structure must reach austenite state. Transition of austenite into martensite is related to carbon diffusion. As final EMSH is one of methods of surface contact hardening using concentrated stream of electrical power, it has certain specific features. The ESH surface hardening cycle including heating
up, exposure, deformation and cooling down takes place in centisecond in the closed zone of thermomechanical contact between the EMSH tool and thread. The temperature in the hardening zone gets as high as 1000…1100 °C and higher. The heated up surface layer is cooled down by means of heat removal by the below layers of metal.

The following formula is used to calculate the amount of heat Q released in the contact zone between EMSH tool and thread and absorbed in the high temperature zone of the thread surface being hardened during the period τ:

\[ Q_T = 0.24 \eta I^2 U^2 \tau k_d k_i, \] (1)

η — coefficient correcting for electric power dissipation in the secondary circuit; I — secondary circuit amperage, A; U — secondary circuit voltage, В; τ — duration of EMSH process, с; k_d, k_i — coefficients correcting for heat removal to the sub and the tool correspondingly.

Alternatively, based on heat-balance equation

\[ Q_T = \delta B \gamma C T_e, \] (2)

\( g = \delta B \gamma \) — high temperature mass (kg); C — specific heat, J/kg°C; \( T_e \) — temperature of metal crystalline transformation, °C; \( B \) — high temperature zone width (m); \( \delta \) — hardening depth (mm); \( \gamma \) — density (kg/m³)

Equating \( Q_T \) into equations (1) and (2) gives us formula for calculating hardening depth based on experimentally-confirmed EMSH modes and sub material characteristics:

\[ \delta = \frac{(0.24\eta I^2 U^2 \tau k_d k_i)}{\delta B \gamma C T_e}, \] (3)

Regression equation of tests for secondary circuit current density \( (X_1) \) and EMSH tool pressing force \( (X_2) \) effect on hardening depth, in coded coefficients values takes the following form (4) Fig. 6.

\[ \delta = 0.2115 + 0.0422 X_1 + 0.0213 X_2 - 0.0004 X_1^2 + 3.8189 \times 10^{-7} X_1 X_2 - 0.0002 X_2^2 \] (4)

**Fig. 6.** Graphic presentation of yield surface of interaction between current density \( X_1 \) and tool pressing force \( X_2 \) in coefficients natural values

The metallographical test results (Fig. 7) indicate gradient structure formed in the hardened layer of thread flanks. Not only the metal structure undergoes changes, but also high dispersed structure of martensite is formed in the surface layer.

Top drive drilling subs P147/147 and P133/133 (Fig. 8) manufactured by NIGMASH LLC in Bashkiria region were field tested by Tatburneft, a division of TATNEFT Public Joint-Stock
Company. The results of the field test confirmed high wear resistance of the threads hardened using EMSH technique. The test results demonstrated more than double increase of make-ups and break-outs of thread connections which was described in the statement of drilling subs connection threads wear resistance field test dated September 7, 2019. Series manufactured subs showed up to 500 load cycles. The two reasons for the subs rejection included wear of external thread and wear of the subs outside diameter.

![Fig. 7. Microstructure of thread flanks after final electromechanical surface hardening](image1)

![Fig. 8. Top drive subs P147/147 and P133/133 after final electromechanical surface hardening](image2)

**Conclusions**

After EMSH technique was applied to external and internal threads of the series made subs they showed 985 cycles of connection make-up and break-out and were rejected due to sub OD wear. No wear were found on the subs connection threads.

The results of these studies and field tests allowed to develop recommendations for using final electromechanical surface hardening method for drilling subs external and internal connection threads hardening on pipe-threading machines.

1. The main reason of the low service life of drill string subs is wear of the external and internal connection threads due to low hardness (30…36 HRC) and insufficient strength of threads after bulk heat treatment.
2. Theoretical and practical studies for hardening of contact surfaces of machines and equipment by using concentrated energy streams demonstrated high efficiency of the EMSH surface hardening method.
3. The studies allowed to develop the technology and equipment for improving wear resistance of drill string subs external and internal connection threads by using final electromechanical surface hardening on pipe threading machines.
4. The research engineers developed the formula for calculating the depth of the hardened layer after the final EMSH hardening. They also determined the effect of the electrical current density in the secondary circuit and of the pressing force in the thermomechanical contact zone between the roller and the thread flank on the hardening depth.
5. Metallographical studies of the structure proved high reproducibility (over 92%) of the theoretical and experimental results related to the connection threads flank surface hardening depth depending on the used mode of EMSH method.
6. The final EMSH technique allowed to increase hardness of the connection thread surface layer from 30–36 HRC to 52–56 HRC to the depth of 0.24 mm and form fine-grained martensite structure to the depth of up to 0.1 mm.
7. Field tests of top drive subs P147/147 and P133/133 made by NIGMASH LLC in Bashkortostan region were performed by Tatburneftcompany, a division of TATNEFT. The subs used in the field test showed 985 cycles of connection threads make-up and break-out and were rejected only because of worn sub OD caused by pipe tong dies.

8. The performed studies and tests resulted proved efficiency of the final EMSH technology for hardening of the drilling subs connection threads. The method can also be used for improving wear resistance of drill pipe and tubing connection threads, as well as ESP housing and various other oilfield equipment.

References
[1] A.I. Yakushev, R.H. Mustayev, R.R.Mavlyutov, Improvement of strength and reliability of thread connections. Moscow, Mashinostroenie, 1979.
[2] A.G. Grigoryants, I.N. Shiganov, A.I. Misyurov, Process technologies of laser hardening. Moscow Publishing House of N.E.Bauman MGTU University, 2006.
[3] V.S. Kraposhin Parameters Selection for Carbon Steels Laser Heating-Up to Achieve Required Hardening Depth. MITOM. 1986, №9.32–35.
[4] V.S. Kraposhin Engineering Formulas for Calculation of Metal Surface Heating Depth with High Concentration Energy Sources. MITOM. 1999, №7.31–36.
[5] V.S. Kraposhin Heating Mode Selection for Heating Using Surface Heating Source to Achieve Required Hardening Depth and Structural Condition. Moscow, Publishing House of N.E.Bauman MGTU University, 2002.
[6] B.M. Askinasi Strength Improvement and Rebuilding of Machine Parts by Using Electro-Mechanical Hardening. B.M. Askinasi. Moscow, Mashinostroenie, 1989.
[7] V.P. Bagmutov, S.N.Parshiev, N.G. Dudkina, I.N. Zakharov, Electro-Mechanical Hardening: Process Technology and Physics, Characteristics, Implementation. Novosibirsk: Nauka Publishing, 2003.
[8] L.V. Fedorova, S.K. Fedorov, Y.N. Kuramshin, M.A. Artemyev, Electromechanical Hardening of Tubing Connection Threads Allows Improving Their Strength and Durability. BureniyeiNeft (2006) №1, 10–12.
[9] L.V. Fedorova, S.K. Fedorov, Technology for Improving Operational Characteristics of Thread Connections by Using Electro-Mechanical Surface Hardening. Machine Building Technologies and Problems. Papers of Visiting Machine Building Session of Principal Council, Ministry of Education of Russia. Ulyanovsk, UGTU (2003) 97–101.
[10] L.V. Fedorova, S.K. Fedorov, A.N. Semyonov, Improvement of Fast Wearing Parts Durability. World Technologies. (2008) №6, 30–32.
[11] L.V. Fedorova, V.F. Karpenkov, S.K. Fedorov, Y.S. Alekseyeva, E.V. Nagnibedova, Technology and Equipment for Improving Strength and Rebuilding of Parts Using Electromechanical Surface Hardening. Machines and Equipment for Agriculture. (2009) №2,34–35.
[12] S.K. Fedorov, L.V. Fedorova, V.T. Sarayev, K.K. Klyuev, Implementing Electromechanical Surface Hardening Technology in Repair Workshop of Syzran Refinery. Scientific and Technical Bulletin of Rosneft Oil Company (2010) No.4, 44–47.
[13] S.K. Fedorov, L.V.Fedorova. Electro-Mechanical Hardening. RITM (2012), No. 2(70).14–16.
[14] L.V.Fedorov, S.K. Fedorov, Y.S.Ivanova, A.M. Lompas, Technology of Parts Wear Resistance Improvement by Using Electromechanical Surface Hardening. Universities New Bulletin. Mashinostroenie Publishing. (2017), №9(690).85–92.
[15] J.S. Alekseeva, L.V. Fedorova, S.K. Fedorov, I.N. Kapustin, Improving the quality of the surface layer of steel parts. Proceeding of 5-th International Mechanical Engineering Forum (IMEF). (2012) Prague, Czech Republic, 65–74.
[16] Fedorov S.K., Fedorova L.V., Ivanova Y.S., Voronina M.V. Increase of Wear Resistance of the Drill Pipe Thread Connection by Electromechanical Surface Hardening. International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 18 (2017) pp. 7485–7489 © Research India Publications.

[17] L.V. Fedorova, S.K. Fedorov, A.A. Serzhant, V.V. Golovin, S.V. Systerov, Electromechanical surface hardening of tubing steels. Metal Science and Heat Treatment. 59(3–4) (2017). 173–175.

[18] S.K. Fedorov, L.V. Fedorova, V.S. Zharennikov, M.V. Pesin, Y.P. Smol'skiy Method of Thread Forming on Parts. Russian Patent No.2482942. (2011). Bulletin №15.

[19] S.K. Fedorov, L.V. Fedorova, V.S. Zharennikov, M.V. Pesin, Y.P. Smol'skiy Method of Thread Forming on Parts. Russian Patent No.2486994. (2011). Bulletin №19.

[20] S.K. Fedorov, L.V. Fedorova, Y.S.Ivanova, A.A. Yakovleva, M.V. Vlasov, V.N. Zaripov, M.A. Lashukov Tooling Unit for Thread Electromechanical Hardening. Russian Patent (2018). No.186927.