# Thermal analysis of a pump used in an innovative installation for cementing and special operations at the oil well intended to improve the efficiency of the extraction of conventional energy resources

**Iulian Cucos**[1,3], **Ion Antonescu**[1,3], **Georgiana Marin**[2] and **Perino Baraga**[3]

**Abstract**

The paper presents a study conducted by the authors for investigating the thermal behavior during operation of the parts of a pump used in an innovative installation for cementing and special operations at the oil well intended to improve the efficiency of the extraction of conventional energy resources, in connection with the structural analysis of that parts in a simulation driven design process. The research looked at the influence of the degree of finishing and the thermochemical treatments of the surfaces of the parts in contact during operation on the thermal regime of these joints in motion and the resulting degree of wear. Simulations were made, using finite element analysis programs, experimental investigations were done, and comparative studies were carried out. Experimental research was carried out to validate of the design and simulation of the components affected by wear due to the thermal effect of the corozive fluids din the triplex plunger pump, the structural and quantitative analysis was performed by electronic microscopy SEM and EDX for determining the composition. chemical of the steel subject to the corrosive and thermal effect of the fluids used in the cementing process, determining the degree of resistance to the corrosive action of the various concentrations of corrosive fluids of the thermochemical treated steel by ionic nitration was highlighted by measuring the hardness of the plunger pump.

**Keywords** Thermal analysis; Installation for cementing; Modeling and simulation; SEM; EDAX; hardness

## Introduction

The cementing aggregates are used in the preparation and pumping of the paste or cement suspensions, pumping the separation fluids and the discharge mud and other special operations (cracking, balancing). The self-portable aggregates are made up of the following basic equipment [22,23,24,27]:

- one or two pressure pumps with plunders or pistons, which provide normal technical parameters to natural aspiration;
- a toothed wheels pump for water supply of the mixture;
- a measurement tank divided into two 100 liter; compartments each, protected against corrosion, through it, filling and alternatively emptying the compartments, measures the volume of mud in the probe to place the paste in the desired space;
- cement mixer with nozzles powered by water by the water pump;
- the manifolds of the aggregate.

For the innovative development of the installation, both the drive with a three-phase asynchronous electric motor included in an electric drive scheme with frequency converter and automation based on data acquisition systems and intelligent sensors, as well as innovative methods of making mechanical subassemblies intended for increasing the working capacity and reducing wear and tear on pumps, plungers, manifolds, valves, gaskets, as well as on the entire installation.

The requirements related to cementing operations and especially to wells were initially analyzed, based on the study of cementing, cracking and acidizing techniques. The knowledge regarding the parameters of the special operations in which the installations are involved was highlighted: pressure, flow, types of fluids used for cementing-fracturing-acidification. It is concluded that for a certain flow rate and pressure, the dimensions of the pump are determined by the length of the stroke and the revolution of the crankshaft, it is necessary to select and use the most appropriate components and an increased resistance to corrosion and abrasion, taking into account the fact that the fluids involved in these operations have a strong corrosive and abrasive effect.

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## The operating principle of the cementation installation

The power needed to train the triplex pressure pump is provided by a engine composed of a diesel or electric motor and hydromechanical or hydraulic transmission, the engine start is done electrically or pneumatically. For starting under low temperature conditions, the engine is equipped with water and oil preheating facility.

The power flow is transmitted from the engine group through a cardan axle to a gearbox/reducer that ensures a different number of speeds, from the gearbox, the power flow is transmitted through a toothed coupling to pump with plunging and elastic coupling at the water pump.

The technical project of a cementing aggregate is presented in Fig. 1 and Figure 2 presents the installation mounted on the truck.

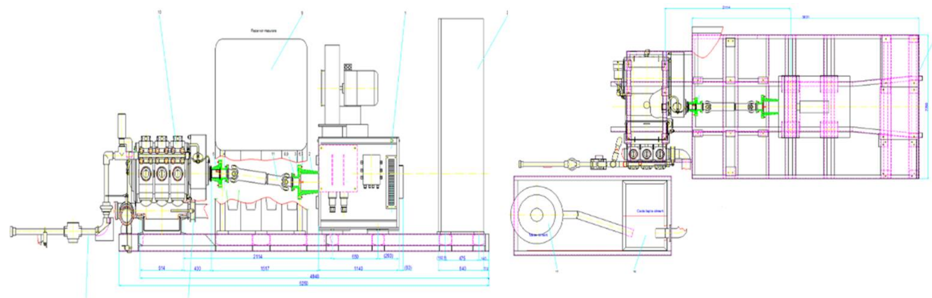


**Fig.1.** Installation for cementing and special operations


**Fig. 2.** The complete installation placed on the truck

The movement received from the transmission is transformed from rotational movement, in the translation movement of the plungers, through a transmission mechanism equipped with gear in "V".

The transmission mechanism is composed of:

- the gear in "V", which has the crowns fixed on the tree cranked by shepherd screws. The axial force developed in each crown pushes the crown to the shoulder of the crankshaft and does not create additional requests in the fixing screws. The direction of training of the pump will not change, in order not to change the meaning of the axial forces.
- the sprocket axis supported on 2 radial rollers that allow it to move the necessary axial to self -centered. The head of the pinion shaft is sealed with the oil bath with a sealing ring that works on a wear bush.
- the connecting rods have sliding camp, at the handle (bimetallic shell of two pieces) and at the head of the spherical joint.
- The head of a cylindrical cross is sliding into a shirt fixed in the body of the fream. Both the head of the cross and the shirt are made by casting, cast iron.

For normal operation between the cross and shirt head, a game of 0.180 - 0.230 mm is provided.

The circulation of fluids is ensured through the manifolds, which allow:

- the aspiration of the pump with plunging from each compartment of the measurement tank, from the fall aspiration for cement milk or from an external source, on both sides of the aggregate;
- reflation of the pump with plunging towards the mouth of the probe, on the barley in the measurement tank or outside. The refuse on the bar is achieved by an adjustable, manually commanded nozzle, which allows a slow and controlled pressure leak;
- feeding each compartment of the measurement tank from the exterior source as well as the independent emptying of each compartment;
- the aspiration of the water pump in each compartment of the measurement and discharge tank to the mixer through a system of water distribution towards the nozzles of the mixer and of recirculating the addition of aspiration.

The command of the aggregate are centralized and can be performed from the podest located around the control desk. At the control desk are mounted both the appliances of the operation of the pump and the water pump, as well as the necessary to follow the operation of the drive engine. In order to follow the discharge pressure, the aggregates are provided with medium insulator and shock absorber, mounted on the pump discharge collector, [1, 27].

## Pumps with plunging used in cementing, cracking equipment

Within this work, only the plunger pump within the cementation installation was studied this is a duplex / triplex pressure pump with simple effect, with cylindrical gear in "V" built especially for the operating regime of the cementing aggregate.

The pumps are designed to operate in a reduced speed (35-200 double/minute races), ensuring a good filling of the pump cylinders and a volumetric efficiency over 0.9 to a natural aspiration without overload. This is a feature, useful because it simplifies the exploitation and increases the field of use of the cementing aggregate. Without diminishing the volumetric efficiency, the hydraulic part of the pump can be equipped, as needed, with Ø 90 mm, Ø100 mm, Ø 115 mm and Ø 125 mm. [1, 27].

The cementing aggregates are used in the preparation and pumping of the cement paste or suspensions (cementation operations), pumping the separation fluids and the discharge mud and other special operations (cracking, balancing).

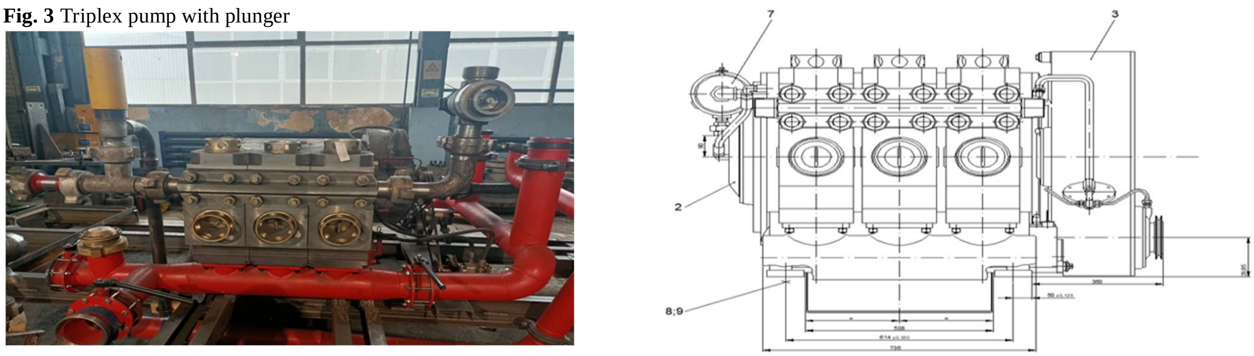
In normal construction, the aggregates are mounted on self -chief, on semi -trailer, or rarely, in the case of marine drilling and isolated or removed locations, on the sleds provided with towing and lifting possibilities.

The self -important aggregates are made up of the following basic equipment: one or two pressure pumps with pluners or pistons, which provide normal technical parameters to natural aspiration; a toothed wheels pump for water supply of the mixer / mixing funnel; a measurement tank divided into two compartments equal to 100 liters grades, protected against corrosion; through it, filling and emptying the two compartments alternately, the volume of mud pumped in the probe is measured to place the paste in the desired space; cement mixer with nozzles (for cementation operation), powered by water by the water pump; the manifolds of the aggregate.

Based on the synthesis performed, the conditions that must be respected have been highlighted for the equipment to ensure the optimal operating parameters in order to successfully carry out the operation:

- the design of the aggregates takes into account the degree of use, taking into account a total number of hours for dimensioning bearings, gears or other organs, much lower than in machines with a continuous operating life and constant load. This hypothesis leads to the creation of component machines of the aggregate, as low as possible, an essential condition for a mobile pumping aggregate.
- it is also taken into account that for a certain flow and pressure, the dimensions of the pump, so its weight are determined by the length of the race and the speed of the crankshaft.
- designing the cementing /cracking operation also involves the selection and use of the most appropriate cracking fluids and support materials. The quantity of these components and the injection mode are essential for the success of the operation.
- the equipment must provide through their components and increased resistance to corrosion and abrasion, taking into account that the fluids involved in these operations have a strong corrosive and abrasive effect.

**Fig. 3** Triplex pump with plunger




a). The physical realization of the designed pump

b). Overall project

**Table 1**. Pumps with plunging use in cementing, cracking equipment

| Aggregate type / pump | Maximum turation at the input pump (rot./min) | Plunger/piston diameter, mm | | | |
|---|---|---|---|---|---|
| | | 100 | | 115 | |
| | | fluid flowl (l/min) | pressure, (bar) | fluid flowl (l/min) | pressure, (bar) |
| ACF 700 Triplex pump with plunging | 204 | 258 | 700 | 296 | 550 |
| | 485 | 412 | 470 | 472 | 350 |
| | 728 | 617 | 310 | 710 | 230 |
| | 971 | 823 | 230 | 945 | 170 |
| | 1457 | 1235 | 150 | 1419 | 120 |
| | 2100 | 1780 | 100 | 2047 | 80 |

## Trends regarding the materials used in the construction of equipment for special operations in wells

The materials used in the construction of the components of the analyzed equipment, have a certain behavior under the attack of the corrosive and abrasive mixtures used in the special operations.

Martensitic stainless steels contain between 12-17 % CR and over 0.1 % carbon. The martensitic steels in a hardened and returned state have a good resistance to corrosion in environments containing nitric acid, carbonates, sulphates. These steels are recommended for the manufacture of elements subject to wear in corrosive environments. The treatment applied should not lead to the separation of chromium carbes, [28]. Reducing the content in chromium below 12 % in certain areas will cause local corrosion. Table 2 presented the main fields of their use.

**Table 2.** Areas of use of martensitic stainless steel steels

| Steel brand | SR EN 10088-1 | Applications |
|---|---|---|
| 35MoCr165 | 1.4122 | Elements that work in water, steam, weak solutions of organic or inorganic acids, subjected to wear by adhesion or erosion, at low temperatures |
| 90VMoCr180 | 1.4112 | Wear -resistant elements in corrosive environments |
| 8Cr170 | 1.4016 | Elements that work in medium aggression environments |

**Table 3.** Composition of commercial packages of inhibitors

| Packages of inhibitors | The quantities of corrosion inhibitors |
|---|---|
| A | 37.85m3 (10 gpt) corrosion inhibitor I and 13.6 kg (30 ppt) reinforcement inhibitor E |
| B | 75.7 kg (20 gpt) corrosion inhibitor II, 9 kg (20 ppt) reinforcement inhibitor E and 227 kg (60 gpt) reinforcement inhibitor F |
| C | 37.85-75.7 kg (10-20 gpt) corrosion inhibitor I and 37-75 kg (10-20 gpt) reinforcement inhibitor G |
| D | 45-55 kg (12-15 gpt) corrosion inhibitor III and 12-15 gpt reinforcement inhibitor H |

Note: gpt = 3.785 m3 corrosion inhibitor to 3785 m3 acid
ppt = 0.4536 kg corrosion inhibitor to 3785 m3 of acid

Each steel sample was previously cleaned by blasting glass balls in order to remove impurities. The samples were weighed before and after testing to determine the weight loss losses. The samples were tested for 6 hours. After testing the samples were cleaned with acetone and slightly farimity to remove the residues of corrosion inhibitors or the film formed during testing. The samples were examined for the evaluation of microscope pitting. The evaluation of the loss of material by corrosion is based on comparison with the level accepted in the industry up to 0.2 kg of corroded material at an area of one square meter [16].
In addition, the evaluation of pitting is made according to the scale presented below. On the pitting scale a value greater than or equal to 2 is considered unacceptable in the case of acidization treatments, even if the loss of corrosion material is within acceptable limits.

**Table 4.** Pitting scale evaluation

| Pitting scale | Interpretation / observations | Pitting scale | Interpretation / observations |
|---|---|---|---|
| 0 | no hole on the surface | 3 | small holes with sizes (1/32 in) 0.79 x$10^{-3}$ m to (1/16 in) 1.5 x$10^{-3}$ m |
| 0-1 | some small shadows on the metal surface | 4 | average holes smaller than (1/16 in) 1.5 x$10^{-3}$ m |
| 1 | small shadows on the surface | 5 | large, deep holes all over the surface |
| 2 | small dots on the surface | | |

Results obtained from the use of different combinations of acids [32]. Through the experiments done it has been shown that when the 13CR steels are exposed to the action of the acidization fluids, depending on the packages of inhibitors used, their behavior in corrosion is completely different.

The recorded results highlighted the following conclusions:

- 5% HCL + 10% acetic acid - the A and B inhibitors packages have failed to protect the steel on corrosion. Even given the concentration of the inhibitor I was 100% no changes in CE2-13CR steels. In the EC1-13CR steel a double amount of inhibitor and increased performances by 38 %, but the loss of material by corrosion remained far beyond the accepted values.

-10% HCl The packages of inhibitors provided protection at the R1-13CR steel and the CE2-13CR steel.

- 15% HCl. By using the inhibitor package C, both 13CR and high ally steel protection has been achieved.

The use of package D provided protection for both the discussed and combination case, 5% HCL + 10% acetic acid. In the presence of inhibitors it can be said that the influence of mechanical properties on corrosion behavior can be ignored, and the loss of material by corrosion is included in standard values.

- 9% HCl +1% HF. The inhibitory package C effectively protects CE1-13CR and CE2-13CR steels. In the other cases the protection failed.

**The technologies of specific treatments applicable to the materials from which the complaints are executed in order to increase the durability**

Regarding the plungers, at the moment the materials are commonly used: OLC 45, 18MNCR11 (18MNCR10) it is an ally for hot processing.

Nitruration is a thermochemical treatment that consists in the enrichment of nitrogen of the superficial layers, in order to improve some surface characteristics, such as hardness, wear resistance, resistance to grip, bending by shock, etc.

In the presence of nitrogen, iron alloys form nitrous and iron carboniters, at low temperatures, which have a hardness and resistance to very high wear. Nitrogen, forms nitrous, finely dispersed, with iron (Fe) and the elements of the Fe, especially aluminum (Al), chrome (CR), vanadium (V). Thus, the following nitrous can be formed [37]. The nitride is done at low temperatures, between 500-580ºC. This avoids the diffusion of nitrogen in the core and the coalescence of the nitrics. It results, a depth of low nitride (usually 0.2-0.6 mm). [36].

Within the present work, the ionic nitrier process is used is based on the principle of luminescent discharge in a rarefied atmosphere. The pieces are arranged at the cathode of a retort, the anode representing the walls of the retort. Between the cathode and the anode there is a light discharge, and a voltage drop that leads to plasma formation is performed. The ions of H and N bombard the piece, producing the increase of the temperature up to 400 - 500 °C and the removal of the Fe atoms.

They form with ions in the iron nitros that are deposited on the piece. The processing duration is reduced (8-12 h), and the quality of the nitrus layer is superior, because it is formed, especially, the phase $\gamma'$. The presence of carbon provides characteristics superior to the nitrus layer by forming Fe3 (C-N) nitri, which is why it is recommended to submit to the nitrurization of the improvement steels (in a state of high quality and return) with a content of 0.4 - 0.7 % C.

A fundamental element of the new innovative solutions is the materials used and the specific treatment technologies applicable to the surfaces of the plungers, the mixing bowl, the manifolds and the screws. In this sense, the trends regarding the materials needed to be used and new technologies, such as nitrating, were studied, with possibilities to determine the quality of the coating in the Company PETAL laboratory.

The identification of innovative methods to optimize the plunger pump was initially developed in the analysis of the sealing system. Based on the results from the specialized literature obtained through modeling and simulations, important conclusions were obtained regarding the constructive form and material of the gaskets, and a new, improved form is proposed for the sealing package as well as for the materials from which it is made.

Triplex pumps are specially built for the operating regime of cementing/cracking aggregates and have the following composition: hydraulic part, hydraulic body, valves, suction manifold, plunger-jacket assembly which are subject to the action of physical and chemical corrosion and abrasion, these are amplified by the thermal effect caused by the friction of the materials involved in the pumping process based on the analysis of the operating conditions of the cracking equipment, the following degradation mechanisms are highlighted:

- if the cementing process involves cement mixtures, additives, considering their abrasive/corrosive nature, the parts and subassemblies that make up the high-pressure pumping system will be exposed to abrasive and corrosive action;
- if the cracking process involves sand-based mixtures, considering its abrasive nature, the transport elements of the sand and additives will be exposed to the action of abrasion wear;
- if the cracking process involves acidification, the parts and subassemblies that make up the high-pressure pumping system are exposed to a strong corrosive action.

To reduce the effects of corrosion, the use of special technologies for covering the plungers, which are tubular in shape and are hard chromed on the outside, the use of stainless steels based on Cr, Ni, especially at the manifolds of the transport system, the use of corrosion inhibitors, alternative chemical treatments, plating dishes with high-density polyethylene.

## Results and discussion

**Modeling and simulation in Solidworks for the components of the innovative cementing plant and special well operations**

A new constructive solution is analyzed and proposed for plunger valves based on conclusions obtained from the theoretical modeling study. For plungers, the analysis indicates the need to use some deposited materials for the substrate and layer, and the technologies of thermal spraying and metallization of the surfaces subject to wear are indicated.

The study dedicated to solutions in the field of introduction of asynchronous motor drive contains elements related to the electric drive components:

- the study of the electric actuation solution;
- the characteristics of the asynchronous motor dedicated to the drive and the establishment of the technical specifications necessary for the design of the drive solution;
- analysis of the static frequency converters that can be used in the engine control respecting the characteristics of the driven pumps;
- solutions of electrical actuation schemes usable for the actuation of the cementing plant for oil wells.

**Materials used and treatments applied**

Metal steel plungers are ideal for applications that require resistance to abrasion, vibration, thermal shock and impact, as well as high mechanical strength.

According to API 674 edition 3 - 2010 art 6.7.2.1, the surface of the metal plunger in contact with the sealing package / gasket set must be hardened or covered. The surface of the plunger in contact with the sealing package must have at least a Rockwell hardness of 35 on the C scale. The surface must be processed so that it has a roughness of Ra < 0.4 μm.

Usually, the metal plungers used in the petroleum field are made in tubular form from alloy steels, such as OLC45 (quality steel with 0.45% C) and 18MnCr11/18MnCr10 (alloy steel for hot processing), which in the classic version are plated on the outside with a hard layer of chrome to increase resistance to wear and corrosion.

Although the solution of plating steel metal surfaces with a hard layer of chromium (VI) for protection against wear and corrosion is a technically viable solution, however, there are elements of risk to the health of operators and the environment due to the toxicity of chromium hexavalent - Cr (VI), which is used during processing. For this reason, worldwide, there have been research and development concerns for new, alternative and ecological solutions since the beginning of the 1990, solutions that are still being developed. Currently there are massive restrictions on the use of processes that lead to Cr (VI) emissions, such as those resulting from plating with a hard chromium layer. One of the procedures for increasing the durability of the plunger surface, which has seen extensive research and development in recent years, is thermal spraying [65].

Thermal spray depositions and thermochemical surface treatments are excellent and viable alternatives to use in place of the hard chrome plating method. In addition to the environmental reasons for using these alternative processes, they offer other advantages such as improved long-term performance: coatings with improved wear behavior, good corrosion resistance, low repair costs and maintenance, optimal level of residual stresses, with significantly improved fatigue behavior, increased lifetime, lower cost prices.

**Finite element simulation of the heat transfer inside the triplex pump with plunger**

The thermal effect caused by the friction of the materials involved in the pumping process of the main parts of the pump component that are subject to the action of physical and chemical corrosion and abrasion was analyzed we have made finite element simulations, using the Solidworks and LISA 8.0.0 software, Figure 4.

Finite element analysis of the thermal stress and demands of plunger pump was performed using specialized software for finite element analysis using the one preprocessor.

The main steps of finite element analysis software are:

a). pattern preprocessing part plunger pump modeling and preprocessing model and creating finite element structure, determine the properties of the material of the piece Figure 5;

b). Processing piece finite element model (FEM).

- establishing the conditions for contour surfaces and values imposed restrictions;

- solving the finite element method (FEM) and display the results for thermal analysis.

Finite element analysis results are presented in the whole volume of the piece and representative sections for drawing conclusions on the analyzed part identifies the most dangerous sections following that on them to carry out thorough investigations.

**Fig. 4.** Triplex pump with plunger

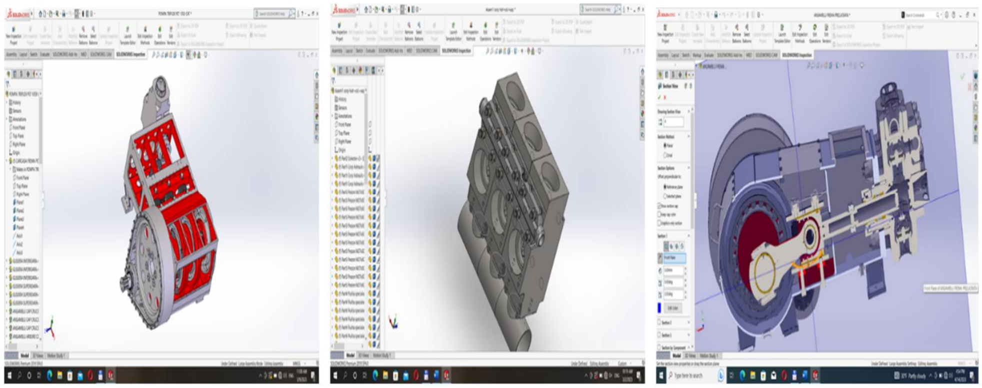
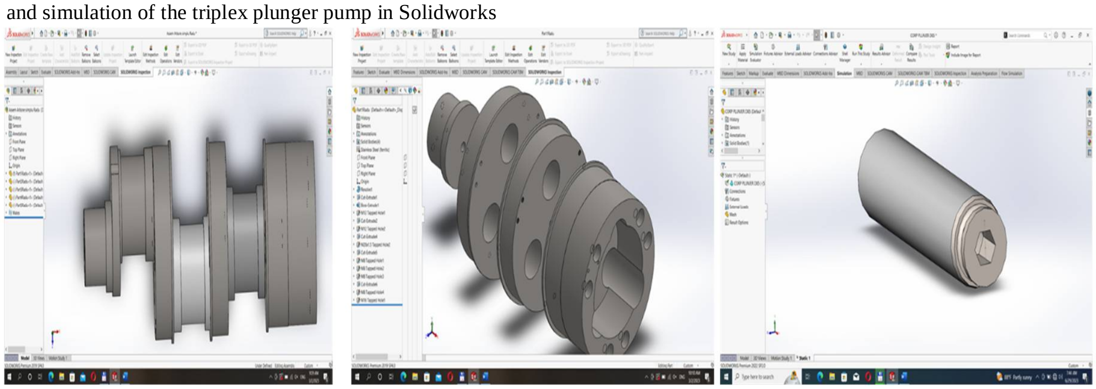
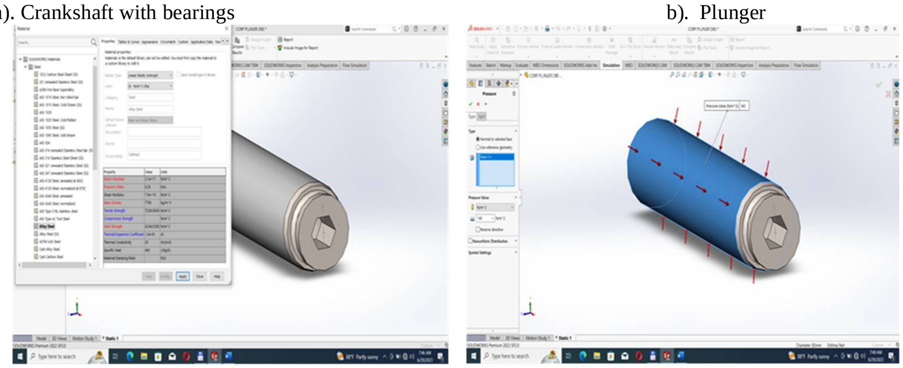


**Fig. 5.** Modeling and simulation of the triplex plunger pump in Solidworks

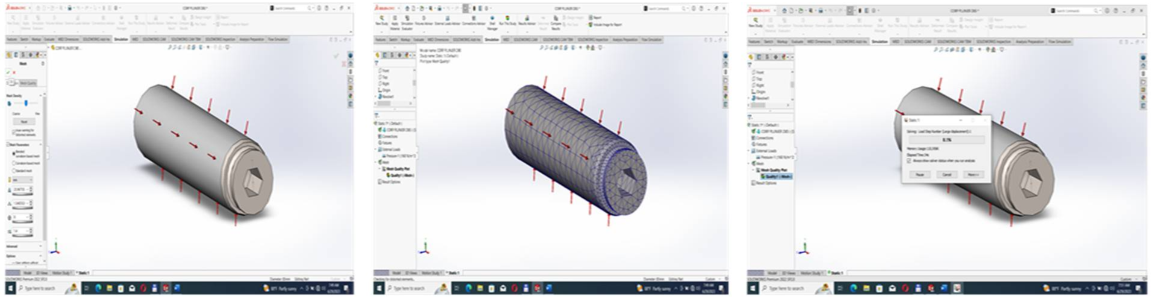


a). Crankshaft with bearings b). Plunger

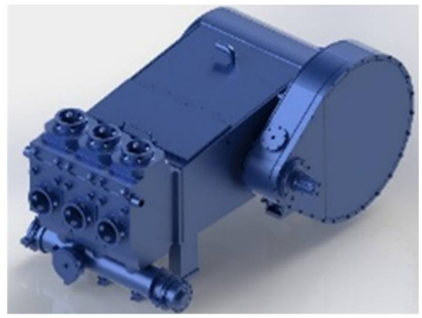
**Fig. 6.** The design and simulation in Solidworks of the components affected by wear due to the thermal effect of the fluids in the triplex plunger pump



a). The finite element mesh and the boundary conditions

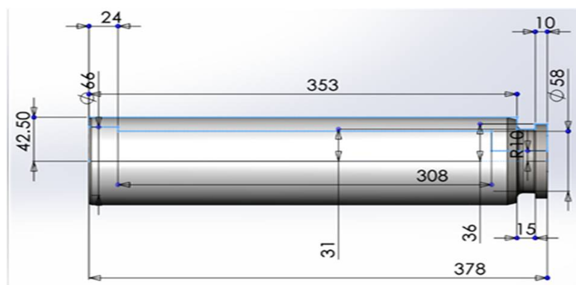


b). running the simulation

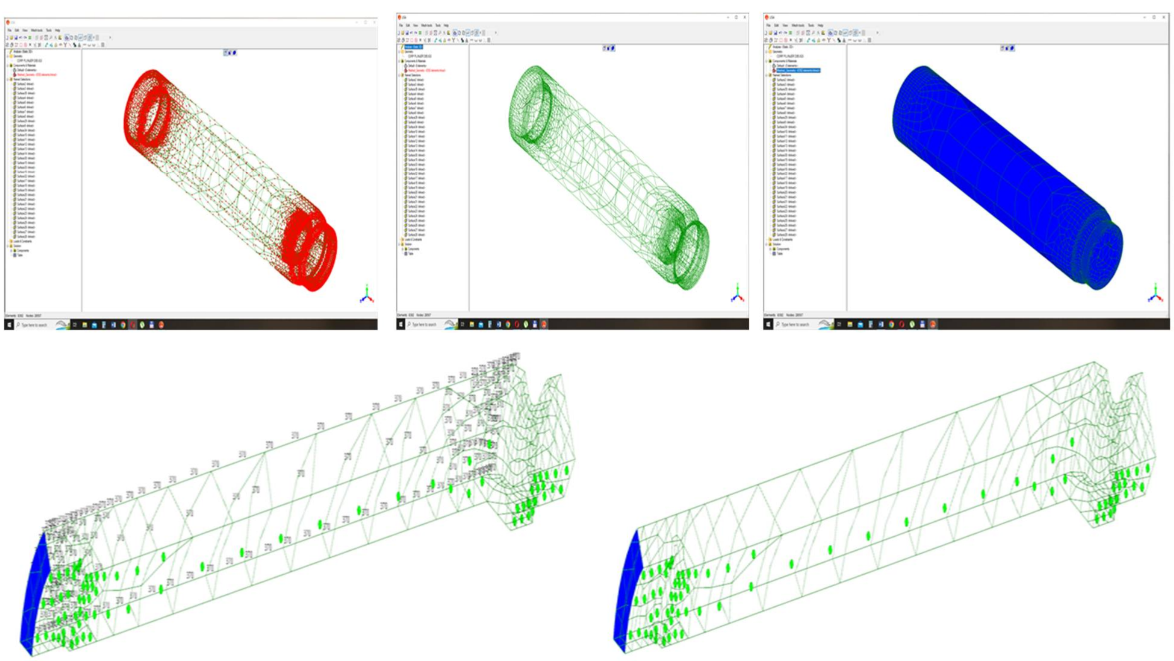


c) the result of simulation

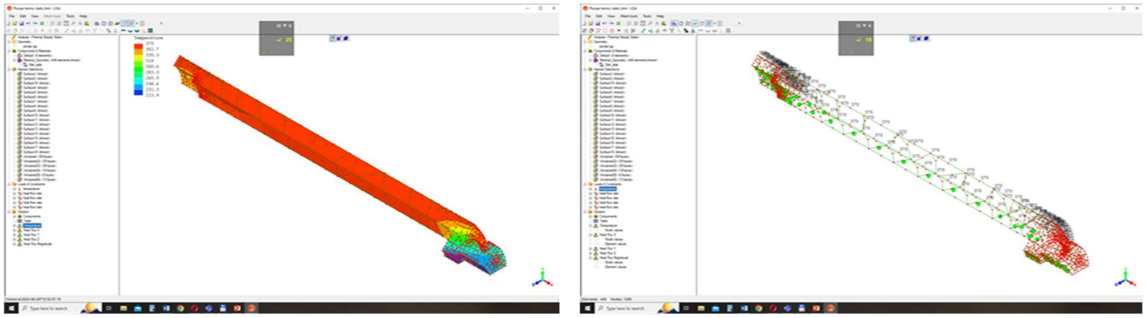
**Fig. 7.** LISA v 8.0 finite element simulation of the plunger



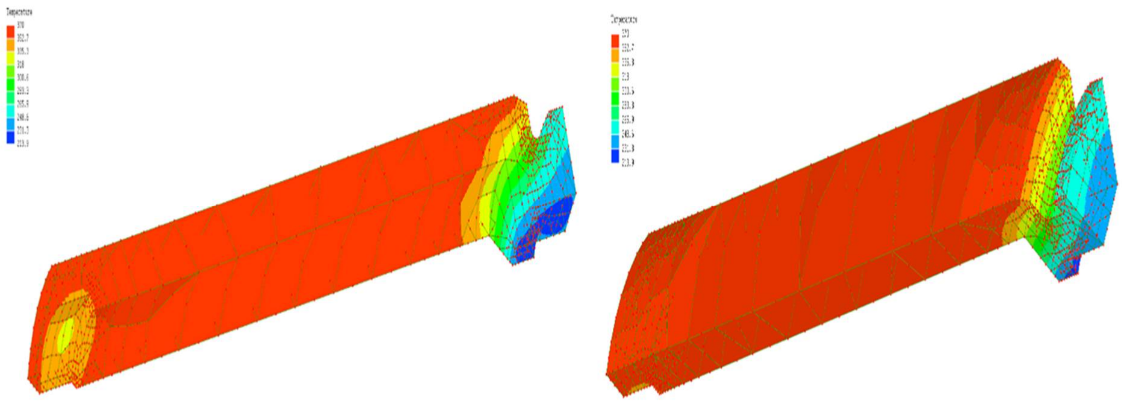

a). Plunger pump and plunger execution drawing



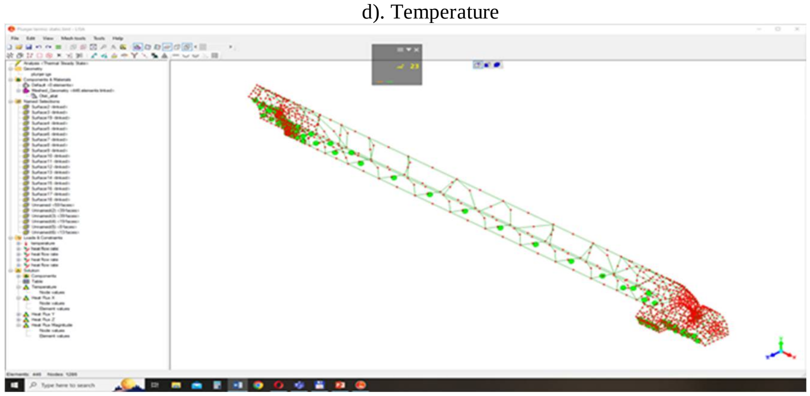
b). discretization and imposition of boundary conditions for the plunger



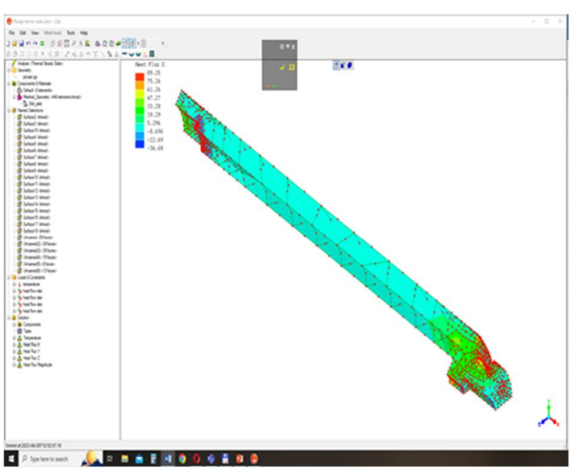
c). thermal analysis for a significant volume of the plunger



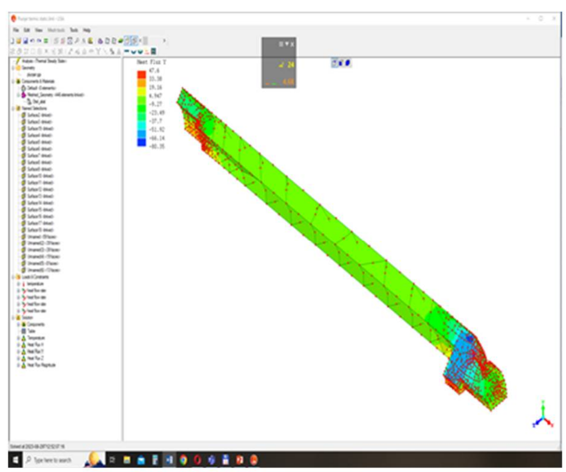
d). Temperature



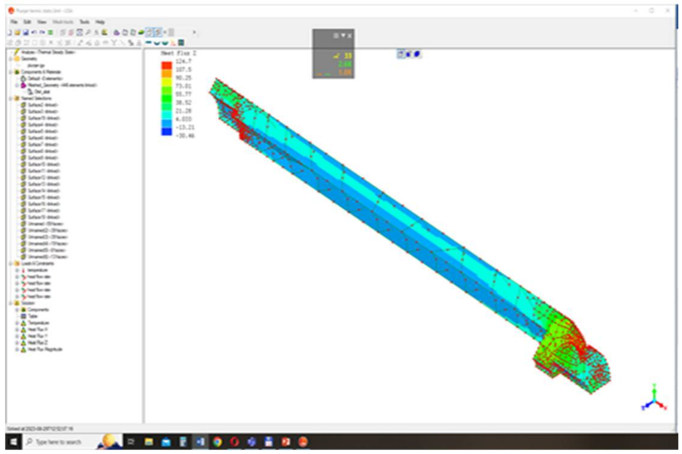
e). Heat flow rate



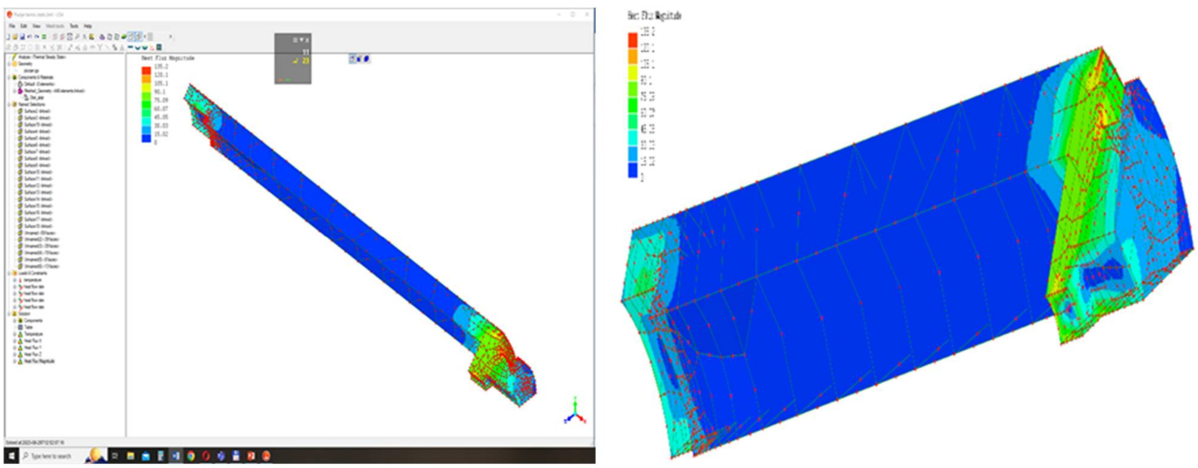
f). heat flow along the X axis



g). heat flow along the Y axis



h). heat flow along the Z axis



j). Heat flux magnitude

**High resistance thermal spraying using forced combustion of oxygen – the HVOF (High Velocity Oxygen Fuel) process**

For the experiments, surface coatings with Mo were made by the three methods on samples of different shapes and sizes adapted to the techniques, methods and standards of analysis or testing applied. For the realization of the preliminary experimental variants of surface coverings, the A5T steel (42CrMo4) currently used for the realization of the drive axles of the metro trains was selected as the support material. Alternatively, a steel with superior properties (34CrNiMo6) was considered for the realization and testing of the optimal molybdenum metallization options. The two types of steel used, Table 5. were in the form of Ø 30 mm rolled bars in annealed condition.

For the preparation of the support materials, it was aimed to determine the optimal thermal treatment conditions for obtaining the mechanical characteristics imposed on the steel from which the tubular axles of the subway trains are made, starting from the premise that after the reconstruction by metallization of the mounting surfaces of the mounted axle, there should be no influences on service requests or projected loads. From this perspective, the experiments to prepare the support materials were focused only on determining the heat treatment conditions that would ensure the designed mechanical properties.

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Table 5. Chemical composition (% mass) of the steels selected for experiments [73]

| EN 10083 | W. Nr. | C | Si | Mn | P | S | Cr | Mo | Ni |
|---|---|---|---|---|---|---|---|---|---|
| 42CrMo4 | 1.7225 | 0,38-0,45 | < 0,40 | 0,60-0,90 | < 0,035 | < 0,035 | 0,90-1,20 | 0,15-0,30 | - |
| 34CrNiMo6 | 1.6582 | 0,30-0,38 | < 0,40 | 0,50-0,80 | < 0,035 | < 0,035 | 1,30-1,70 | 0,15-0,30 | 1,30-1,70 |

In order to evaluate the metallized layers, the following morpho-structural and mechanical characteristics were investigated, considered to be essential for validating the optimal solution of surface coatings for the protection and dimensional reconstruction of the components:

- microstructural characterization by analyzing and processing SEM images (surface and cross-sectional microstructural characteristics, porosity, substrate-coating adhesion/coating layers, thicknesses and diameters of splats, cracks, inclusions, etc.);
- topographic characterization of the coatings (roughness determined by mechanical palpation, 1D and 2D roughness determined based on three-dimensional images - stereo images);
- vickers microhardness measurements;
- determination of the modulus of elasticity;
- determination of the breaking toughness of the coatings;
- determination of adhesion resistance on raw and rectified surfaces with thicknesses of the metallized layer in the range of 100 - 600 μm;

The results obtained during the experiments highlighted: the investigated Mo metallized layers present particular microstructural characteristics determined by the thermal spraying methods used, characterized by successive layers of flattened particles, scattered upon impact with the substrate, with porosities, cracks and oxidized particles.

Although all three methods result in metallized layers with a similar anisotropic structure, the flattened particle sizes are inversely proportional to the impact energy determined by the thermal spraying method: at high impact energies (HVOF) smaller flattened particle sizes result (Daverage = 37 μm), compared to the APS method (Dmean = 93 μm) and electric arc (Dmean = 138 μm).

The same tendency was determined for the thickness of the flattened particles (h) and the degree of deformation of the particles ($\xi$).

A direct correlation was determined between the sizes of the flattened particles and certain intrinsic properties of the metallized layers: in the case of smaller sizes (HVOF), more compact and denser coatings result, with higher tenacity, with a level of internal porosity and a higher surface roughness reduced, compared to the coatings obtained by electric arc or plasma jet.

Although metallization by APS produces flattened particles of smaller sizes, coating layers with greater compactness and a lower level of porosity than in the case of the electric arc metallization method, the difference of approx. 1% regarding the determined value of the density (8.86 g/cm3 for APS and 8.97 g/cm3 for AE) can be associated with a higher content of oxidized particles in the coating layer.

The much higher spraying temperature in the case of the APS process generates a higher content of Mo oxides which have a much lower density than pure Mo. As a general finding, in the case of layers deposited by thermal spraying by different methods, the presence at the microstructural level of oxide inclusions, pores and discontinuities that generate different levels of compactness, the determined values of the density are lower than those of the pure metal from which originate

Determining the fracture toughness by microindentation of the investigated metallized layers showed a tendency to increase the fracture toughness values depending on the indentation load, in both indentation directions (parallel and perpendicular to the interface with the substrate), for all three types of coatings of molybdenum.

The evaluation of the usage properties of the molybdenum coatings, adhesion resistance and tribological properties, revealed the fact that larger sizes of the flattened particles obtained by electric arc spraying determine a better behavior of the metallized layers.

In order to evaluate the specific rate of wear for the layers metallized with Mo by the three thermal spraying methods used, additional micro-abrasive wear tests were carried out for the same friction duration of 900 sec. corresponding to the transition point between the break-in period and the stable wear period, previously determined. For comparison, a set of determinations was also performed on 34CRNiMo6 steel samples; 42MoCr4 unmetallized.

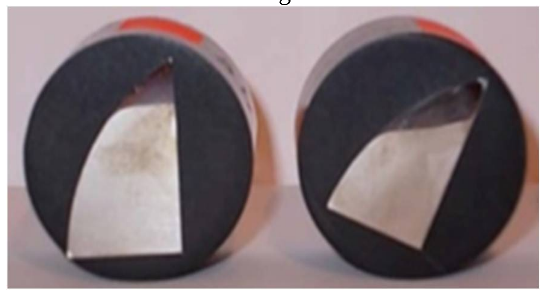
The experimental results indicate that the specific rate of wear for samples metallized with Mo by electric arc is lower than in the case of metallization by APS.


**Fig. 8.** Procedeu de depunere HVAF prin pulverizare a carburii de wolfram pe un plunger de pompa [76]

**Analysis of samples of heat treated parts by electron microscopy SEM and EDAX spectrometry**
For the tests and experimental measurements were used samples of plunger made of steel C45-RO1.0503
Micro structural analysis of plunger, was performed on a scanning electron microscope VegaTescan LMH II SEM, working - 46 High using detector type LFD (Large Field Detector), acceleration voltage electron beam used was 30 kV, and working distance was 15 mm. From the analysis of samples by electron microscopy SEM shows that if the heat treatment

of pearlite grains are coarse classic uniformly distributed in the ferrite matrix therefore blade material's mechanical properties are reduced, the piece has a reduced durability and low mechanical strength.

**Fig. 9.** The test pieces taken from heat-treated



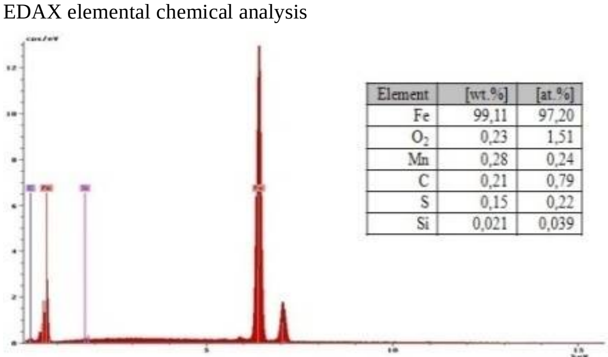
EDAX analysis was performed on the sample surface layer to highlight its chemical composition is observed the presence of chemical elements Fe, C, Mn, S, Si and $O_2$ in different proportions corresponding to the chemical composition of steel C45-RO1.0503. Determination of chemical composition of the material for plunger EDAX spectrometry was performed on a scanning microscope SEM electrons VegaTescan LMH II concentrations determined by mass spectrometry EDAX elements of sample material taken from the plunger specified in table 6. Bruker Quantax AXS Microanalysis GmbH, Germany
Results Acquisition 4588 Date: 26/09/2023

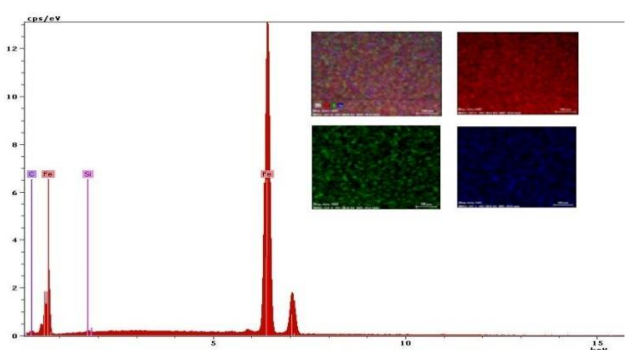
**Table 6** Chemical composition of the material sample in percent by mass.

| Element | AN | Net | [norm. wt.%] | [norm. at.%] | Error in % |
|---|---|---|---|---|---|
| Iron | 26 | 145203 | 99,106 | 97,202 | 2,54 |
| Oxygen | 8 | 3832 | 0,227 | 1,508 | 1,02 |
| Manganese | 25 | 5935 | 0,284 | 0,237 | 0,14 |
| Carbon | 6 | 1756 | 0,208 | 0,795 | 0,48 |
| Sulfur | 16 | 2605 | 0,154 | 0,219 | 0,10 |
| Silicon | 14 | 206 | 0,021 | 0,039 | 0,05 |
| | | Sum: | 100 | 100 | |

In samples from the furnace heat treated plunger management system based on a step predictive algorithm is found that iron is observed following elemental analysis is found uniformly distributed in the base material as can be seen in the distribution map. The oxygen is uniformly distributed in the base material at many generally it is in the form of oxides. Carbon is present in the iron alloy, uniformly distributed, but is observed uniformly dispersed islands alloys thereof chemical compounds with Mn, S and Si. Manganese is contained in the form of islands uniformly dispersed large mass of the base material.
Sulfur is a small scale and appears in different alloys with Fe, Mn, C, uniformly dispersed in the base material.
Silicon is insignificant and appears only as an alloying element to the base material.
Chemical and elemental analysis, samples taken from plunger, heat treated in a furnace that has implemented a management system structure predictive control algorithm based on a step is shown in Figures 10 and 11.

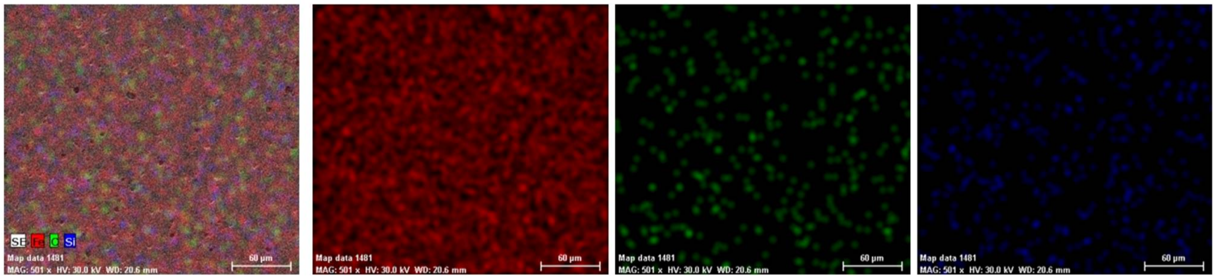
**Fig. 10** Map of the distribution of chemical elements for the piece EDAX elemental chemical analysis a) SEM image b) EDAX elemental chemical analysis



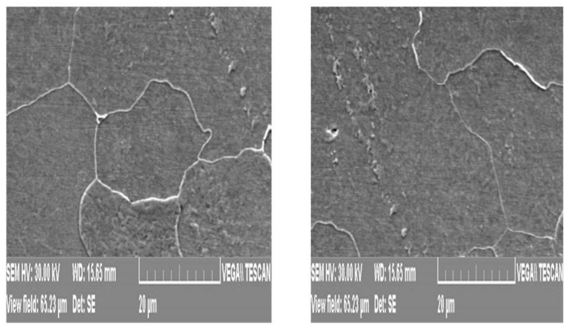
Microstructures analysis of low power plunger made of steel C45-RO1.0503, performed on a scanning microscope SEM electrons VegaTescan LMH II are shown in the following figure.
Name of sample material: steel C45-RO1.0503
Chemical composition: C = 0.49%; Mn = 0.24%; Si = 0.039%; S = 0.22%
Scanning electron microscopy (SEM)
Length bar: 20 µm
Description: carbon steel microstructure - ferrite and pearlite grains distributed in plunger.

**Fig. 11.** Map of the distribution of chemical elements for the piece heat treated




all elements map    Fe map    C map    Si map

**Fig. 12.** SEM image of pale material heat treated in heat treatment furnace temperature sensitive thermostatic controlled with a PID one step ahead controller




*a) micrographs M1*    *b) micrographs M2*

From the analysis of samples by electron microscopy SEM shows that if the heat treatment of pearlite grains are coarse classic uniformly distributed in the ferrite matrix therefore plunger material's mechanical properties are reduced, the plunger has a good running low, low durability and low mechanical strength.
We mention that there is an compliance reliably between hardness and mechanical characteristics and plasticity of the plunger so resistance high hardness and a uniform distribution of microcrystalline phases (ferrite and pearlite) ensures high durability and toughness to play a positive effect on time to good works plunger simultaneously increasing the capacity of taking hydraulic shock due to fluid flow in pump, also increases resistance to corrosion and cavitations wear the plunger.
The experimental results are taken from data acquisition board installed in the control system of electric furnace for heat-sensitive treatments. The chemical, physical, mechanical and structural were highlighted by experimental laboratory determinations were performed on standard test specimens, specific tests.
Determination of chemical composition by EDAX spectrometry allowed a comparative analysis of the distribution of chemical elements in samples of material palettes microcell reveals the fact that if the heat-treatment furnace control system based on predictive algorithm on a step more uniform dispersion of chemical elements is relatively samples heat treated in an furnace with PID control system that enables the conversion of a greater percentage of austenite pearlite dispersed to obtain uniform fine structure that leads to an improvement of the mechanical properties of the part.
From the analysis of samples by electron microscopy SEM shows that if the heat treatment of pearlite grains are coarse classic uniformly distributed in the ferrite matrix therefore plunger materials mechanical properties are reduced, the plunger has a good running, low durability and low mechanical strength.
If the heat treatment temperature sensitive heat treatment furnace realized ordered thermostatic control systems with PID one step ahead structure of the material consists of fine pearlite crystalline grains uniformly distributed in the ferrite matrix, the mechanical properties are superior parts have a resistance high mechanical wear and high toughness.

## Conclusions

The carrying out of cementing and cracking operations at the oil well requires specific conditions that require the establishment, on a scientific basis, of the criteria for the selection and efficient use of the related equipment, the equipment/aggregates are characterized by the maximum pressure, this parameter being also a coding index. In principle, aggregates with pressures up to 700 bar are intended for cementing operations, those with pressures greater than 700 bar are also intended for cracking operations.

The operating time of the cementing or fracturing aggregate is much lower, compared to that of the drilling machines, being estimated at approximately 1500 hours annually. Of this working time, the operation of the aggregate at maximum parameters represents a fraction of the order of 20-30%.

The equipment must ensure the optimal operating parameters in order to carry out the operation successfully, the design of aggregates takes into account the degree of use, taking into account a total number of hours for the dimensioning of bearings, gears or other organs, much less than for machines with a continuous operating time and constant load. This hypothesis leads to the creation of equipment components of the aggregate, with as little weight as possible, an essential condition for a mobile pumping aggregate.
It is also taken into account that for a certain flow rate and pressure, the dimensions of the pump, and therefore its weight, are determined by the length of the stroke and the speed of the crankshaft.

- the design of the cementing/fracturing operation also involves the selection and use of the most appropriate fracturing fluids and support materials. The quantity of these components and the way of injection are essential for the success of the operation.

- the equipment must ensure, through their components, an increased resistance to corrosion and abrasion, taking into account the fact that the fluids involved in these operations have a strong corrosive and abrasive effect.

Within the work, the materials used and the coating techniques with corrosion and wear -resistant layers are approached to increase the durability of the plunger, key element in the functioning of the pump with high pressure. A large analysis of the thermal spray procedures used in recent years with very good results in the practice of the execution of the complaint has been performed. They were identified and selected as representative: thermal spraying / metallization with flame (fuel) high -speed (HVOF) and high resistance thermal spray using a lower oxygen concentration - HVAF. All the components of the equipment for which innovative solutions and integrated novelty elements were presented were presented, so for the triplex pump with plunging: they were studied:
- various constructive variants for the sealing package of the plunger, integrated according to the conditions that will be established in the design stage (working pressures)
- Constructive solutions for Plunger, integrated according to the conditions that will be established in the design stage
- treatments for the protection of metal complaints against corrosion and wear;
- Treatments to increase the durability of the plunger surface by depositing under plasma jet
- The use of modern materials identified in the study for plunging considering the behavior of the substrate material for different applicable treatments.

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**Author contributions**
All authors contributed equally to the realization of the scientific article.

**Data availability** Data will be made available on request.

## Declarations

**Conflict of interest** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## References

1 Adam A., Composite layered material - Invention patent " No. 119 604 B, 28.02. 2000;
2 Alok Satapathy, - Thermal spray Coating of Red Mud on metals, Department of Mechanical Engineering National Institute of Technology Rourkela, India, November, 2005;
3 Anton Paar GmbH, Viscosity of Crude Oil, 2020, https://wiki.anton-paar.com/en/crude-oil/
4 Atanasiu, V., A. Purcel - Oil extraction practice - Technical Ed 1971;
5 Brinke T., Plasma-Assisted Nitriding Offers Production Flexibility, Industrial Heating, May 2001, https://www.industrialheating.com/articles/84271-plasma-assisted-nitriding-offers-production-flexibility
6 Brooks, B.E., Beckermann, C., 2013. Prediction of Heat Treatment Distortion of Cast Steel C-Rings, in Proceedings of the 61st SFSA Technical and Operating Conference, Paper No. 4.5, Steel Founders Society of America, Chicago, IL, pp. 1-30.
7 Byrne JH, Yang CFM. Plunger packing with wedge seal having extrusion recess. WIPO Patent No. 2012083179; 2012.
8 Carfi G.R., P.G. Cirimello, A. Cabo, Plunger with ion nitriding treatment for a hydraulic fracturing pump and a method for making said plunger, United States Patent Application US 2017/0082194 A1, March 17, 2017, https://www.freepatentsonline.com/y2017 /0082194.html
9 Carlone, P., Palazzo, G. S., 2011. Development and Validation of a Thermo-Mechanical Finite Element Model of the Steel Quenching Process Including Solid-Solid Phase Changes, Int. Apag.l. Mech. 46, pp. 955-971.
10 Chen X, Hao M. Development and application of PTFE graphite composite castings. Fluid Mach 2001;7:8–10.
11 Chi M. Analysis and countermeasures of high-pressure plunger injection pump seal. Pump Technol 2003;5:38–40.
12 Chuanxian, H. Bingtang , L. Huiling, 1984, Thin Solid Film, v 118, ;
13 Cinco, Ley, F. Samaniego, Transient Pressure Analysis for Fractured Wheels, JPT, 1749-1766 – September 1981;
14 Coloja, M.P., C. Popescu, Extraction of crude oil and associated gases - Technical Ed., Bucharest 1993;
15 Cristescu M., Oil extraction. Stimulation operations, intervention and repairs, Publishing House of the Petrol-Gaze University of Ploiesti, 2009, ISBN 978-973-719-298-1, https://www.academia.edu/13505942/Dictionar_de_petrol_interventii
16 Dawson, J., Pipeline Corrosion Management, PII Limited, United Kindom;
17 Dorman, J., F. Udvary, Comparative Evaluation of Temporary Blocking Fluid Systems for Controlling Fluid Loss Through Perforations, SPE Paper No. 31081, presented at the 1996 SPE International Symposium on Formation Damage Control, 14-15 February 1996, Lafayette, LA;

18 Economides M.J., Mc. Lennan, J.D. Brown, Roegiers, Performance and Stimulation of Horizontal Wells - Part 1, World Oil, June 1989, Part 2 World Oil, July 1989;
19 Economides M.J., Hydraulic Fracturing for Well Stimulation - 3rd ed. Wiley New York, 1991, End; Petroleum 4 (2018);
20 Fink J.- Petroleum Engineer's Guide to Oil Field Chemicals and Fluids, Elsevier 2012;
21 Gilstad BC, Gilstad DW. Plunger seal ring. U.S. Patent No. 8,276,918; 2012.
22 Heiman R.B., 'Plasma Spray Coating, Principle and Application', VCH, Weinheim, Germany, 1996
23 Herbert H. Tackett Jr., James A. Cripe, Gary Dyson, Positive displacement reciprocating pump fundamentals – power and direct acting types, Proceedings of the twenty-fourth International Pump Users Symposium, Houston Texas, 2008;
24 Hojmrle K. and M. Dorfman, 1985, Mod. Dev. Powder. Met., v 15(15),;
25 Hubbert M.K, D.G. Willis, Mechanics of Hydraulic Fracturing, Trans. AIME 210 , 152 – 168 , 1957;
26 Johnson B.V., M.J Ghafri., Al-harthy A.S.M. - The Use of Carbon Steel in Highly Sour Oil and Gas Production Systems - prepared for presentation of the SPE International Oilfield Scale Conference held in Aberdeen UK, 28 -29 May 2008;
27 Lesto A., Prabhancana Kusumo, D. Supriyatman,- Corrosion Management in Production Pipeline Network Using Risk Management Analysis" prepared for presentation at the SPE Asia Pacific Oil and Gas Conference and Exhibition held in Jakarta, Indonesia, 15–17 April 2003;
28 Macovei N, Tubing and cementing of wells - Publishing House of the University of Ploiesti 1998;
29 Marin, G.- Studies and research regarding the realization of a transportable installation for inserting flexible tubing into wells under extraction, including the eruption prevention system, jubilee session OF "PETROL-GAZE" UNIVERSITY Ploiesti, OIL Equipment section for extraction drilling, Ploiesti 1998
30 Marin, G.- Technologies and equipment for the directed drilling of under-crossing holes, EXPO PETRO GAS SYMPOSIUM - EDITION 3, Bucharest, Sept. 2000
31 Mingjie K, J. Bales, Corrosion Behavior of Various 13 Chromium Tubulars in Acid Stimulations Fluids, presented at 1st International Symposium on Oilfield Corrosion held in Aberdeen 2004;
32 Miron C., Methods, technologies and products for restoring and increasing the natural permeability of the strata in order to increase the influx of oil and gas and the receptivity of injection wells Technical Publishing House, Bucharest, 1999;
33 Montgomery C., Fracturing Fluid Components. In Effective and Sustainable Hydraulic Fracturing 2013 May 17. IntechOpen, https://www.intechopen.com/books/effective-and-sustainable-hydraulic-fracturing/fracturing-fluid-components
34 Prantil, V. C., Callabresi, M. L., Lathrop, J. F., Ramaswamy, G. S., Lusk, M. T., 2003. Simulating Distortion and Residual Stresses in Carburized Thin Strips, ASME, J. Eng. Mater. Technol. 125(2), doi:10.1115/1.1543973, pp. 116-124.
35 Restarick, H.L., Mechanical Fluid-Loss Control Systems Used During Sand Control Operations, SPE 23741 paper presented at SPE International Symposium on Formation Damage Control, Lafayette, LA, February 26-27, 1992;
36 Serban V., A. Raduta, "Politehnica" University of Timisoara, Materials Science and Engineering, Edition III, Politehnica Publishing House 2014;
37 Serban V., "Politehnica" University of Timisoara, Course 13, 2009, http://www.mpt.upt.ro/doc/Curs%20finale%20IE-%202012.ppt
38 Serban V., "Politehnica" University of Timisoara, Materials Science, Course "Thermal treatments applied to Fe-C alloys", https://drive.google.com/file/d/0BxVb8sILHHT1YUlxd1RWNDZtbmM/view
39 Silvana Rossy Brito, Ivan Bastos, Hector Reynaldo Meneses Costa, José Brant de Campos, "Correlation Between Chemical Composition and Adherence of Cr and Co Coatings Deposited by Electric Arc", Journal of Adhesion · May 2014;
40 Suciu V., M.V. Suciu, Studiul Materialselor, Ed. Fair Partners, 2008, 255 pages, ISBN 978-973-1877-01-3, http://marcel.suciu.eu/Cartea_Std_Mater.pdf
41 Sunshil, S., 2012. Review of heat transfer augmentation for cooling of turbine blade type by geometrical modification to the surfaces of blades, International Journal of Research in Engineering and Technology, ISSN 2319-1163.
42 T. auf dem Brinke, Plasma-Assisted Nitriding Offers Production Flexibility, Industrial Heating, May 2001, https://www.industrialheating.com/articles/84271-plasma-assisted-nitriding-offers-production-flexibility
43 Tremoulet O, Raghavan C, Madden K. Plunger seal assembly for a high pressure pump. WIPO Patent No. 1999014501; 1999.
44 Tudor I., G.V Rapeanu, Corrosion Engineering, vol 1-2, Publishing House of the University of Ploiesti 2002;
45 Utu Dragos, "Habilitation thesis - Coating and remelting techniques with layers resistant to corrosion and wear" Universitate Politehnica Timisoare 2019; http://docplayer.ro/178445172-Tez%C4%83-de-abilitare-conf-dr-ing-ion-drago%C8%99-u%C8%9Bu-universitatea-politehnica-timi%C8%99oara- faculty-of-mechanic%C4%83.html ;
46 Uțu I.D., I. Mitelea, Introduction to Surface Engineering, Politehnica Timișoara Publishing House, 2018;
47 Vetter J., J. Crummenauer, T. auf dem Brinke, Corrosion Protection by Plasma Heat Treatment IONIT OX®, AMS/TMS Fall Meeting Conference, Columbus, Ohio, Oct. 2002, https://www.researchgate.net/publication/260016884_Corrosion_Protection_by_Plasma_Heat_Treatment_IONIT_OXR
48 Vetter J., Thermochemical Heat Treatment with Added Corrosion Protection and Wear Protection ICMCTF Conference, April 2003, San Diego, https://www.researchgate.net/publication/260035060_Thermochemical_Heat_Treatment_with_Added_Corrosion_Protection_and_Wear_Protection_-_invited_talk_ICMCTF_2003_San_Diego
49 Wang C. A. Neville, Understanding Inhibitor Action on Components of Erosion, Corrosion and their Interactions in CO2 -containing Slurries, presented at 1st International Symposium on Oilfield Corrosion held in Aberdeen 2004;
50 Yang J, Yu Z, Fei X, et al. Technical progress of hydraulic reciprocating seals.
51 Yi Zhou, Zhiqiang Huang, Yan Bu, Chengsong Qiu, Yuan Yuan, - Simulation studies on drilling mud pump plunger seal failure under ultrahigh pressure and ultradeep conditions, Elsevier, 2014.
52 Zhanghua Lian a, Yang Liu a, Tiejun Lin a, Li Li b, Zhongqing Lei c, Chuanjun Han - Study on the fluid flow rule of five-cylinder plunger pump hydraulic, End Petroleum 4 (2018).
53 Zhu Weibing, Yan Jingjiang, Heshun Wang - Structure Analysis and Design Improvement of Plunger Seal Pair in Fracturing Pump, American Journal of Engineering and Technology Management, Volume 1, Issue 3, October 2016.
54 *** Handbook of Thermal Spray Technology, ASM International, Edited by J.R. Davis
55 *** http://kermetico.com/hvaf-vs-hvof-coating
56 *** http://www.comoti.ro/ro/Proiect_METAXLE.htm?pag=3
57 *** http://www.confind.ro/hvof.html
58 ***www.hunprenco.com/process/details/hvof_high_velocity
59 *** https://kermetico.com/applications/pump-plunger-coating-equipment
60 *** https://plasmajet.ro/metalizarea-cu-plasma/
61 *** 1991. ASM Handbook, Vol. 4: Heat Treating, ASM International, ASM International Library of Congress.
62 *** 2014. Matlab-Simulink (MATLAB®) (http://www.mathworks.com/control-systems)
63 *** Technical book ACF 700, ACF 800 - IPCUP Ploiesti Archive;
64 *** Earthworks, Hydraulic fracturing, Issue 101, Dec. 2017, https://www.earthworks.org/issues/hydraulic_fracturing_101/#FOOTNOTE1

# Journal of Thermal Analysis and Calorimetry


## Thermal analysis of a pump used in an innovative installation for cementing and special operations at the oil well intended to improve the efficiency of the extraction of conventional energy resources

--Manuscript Draft--

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| Suggested Reviewers: | |

# Thermal analysis of a pump used in an innovative installation for cementing and special operations at the oil well intended to improve the efficiency of the extraction of conventional energy resources

**Iulian Cucos**[1,3], **Ion Antonescu**[1,3], **Georgiana Marin**[2] and **Perino Baraga**[3]

**Abstract**

The paper presents a study conducted by the authors for investigating the thermal behavior during operation of the parts of a pump used in an innovative installation for cementing and special operations at the oil well intended to improve the efficiency of the extraction of conventional energy resources, in connection with the structural analysis of that parts in a simulation driven design process. The research looked at the influence of the degree of finishing and the thermochemical treatments of the surfaces of the parts in contact during operation on the thermal regime of these joints in motion and the resulting degree of wear. Simulations were made, using finite element analysis programs, experimental investigations were done, and comparative studies were carried out. Experimental research was carried out to validate of the design and simulation of the components affected by wear due to the thermal effect of the corozive fluids din the triplex plunger pump, the structural and quantitative analysis was performed by electronic microscopy SEM and EDX for determining the composition. chemical of the steel subject to the corrosive and thermal effect of the fluids used in the cementing process, determining the degree of resistance to the corrosive action of the various concentrations of corrosive fluids of the thermochemical treated steel by ionic nitration was highlighted by measuring the hardness of the plunger pump.

**Keywords** Thermal analysis; Installation for cementing; Modeling and simulation; SEM; EDAX; hardness

## Introduction

The cementing aggregates are used in the preparation and pumping of the paste or cement suspensions, pumping the separation fluids and the discharge mud and other special operations (cracking, balancing). The self-portable aggregates are made up of the following basic equipment [22,23,24,27]:

- one or two pressure pumps with plunders or pistons, which provide normal technical parameters to natural aspiration;
- a toothed wheels pump for water supply of the mixture;
- a measurement tank divided into two 100 liter; compartments each, protected against corrosion, through it, filling and alternatively emptying the compartments, measures the volume of mud in the probe to place the paste in the desired space;
- cement mixer with nozzles powered by water by the water pump;
- the manifolds of the aggregate.

For the innovative development of the installation, both the drive with a three-phase asynchronous electric motor included in an electric drive scheme with frequency converter and automation based on data acquisition systems and intelligent sensors, as well as innovative methods of making mechanical subassemblies intended for increasing the working capacity and reducing wear and tear on pumps, plungers, manifolds, valves, gaskets, as well as on the entire installation.

The requirements related to cementing operations and especially to wells were initially analyzed, based on the study of cementing, cracking and acidizing techniques. The knowledge regarding the parameters of the special operations in which the installations are involved was highlighted: pressure, flow, types of fluids used for cementing-fracturing-acidification. It is concluded that for a certain flow rate and pressure, the dimensions of the pump are determined by the length of the stroke and the revolution of the crankshaft, it is necessary to select and use the most appropriate components and an increased resistance to corrosion and abrasion, taking into account the fact that the fluids involved in these operations have a strong corrosive and abrasive effect.

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### The operating principle of the cementation installation

The power needed to train the triplex pressure pump is provided by a engine composed of a diesel or electric motor and hydromechanical or hydraulic transmission, the engine start is done electrically or pneumatically. For starting under low temperature conditions, the engine is equipped with water and oil preheating facility.

The power flow is transmitted from the engine group through a cardan axle to a gearbox/reducer that ensures a different number of speeds, from the gearbox, the power flow is transmitted through a toothed coupling to pump with plunging and elastic coupling at the water pump.

The technical project of a cementing aggregate is presented in Fig. 1 and Figure 2 presents the installation mounted on the truck.

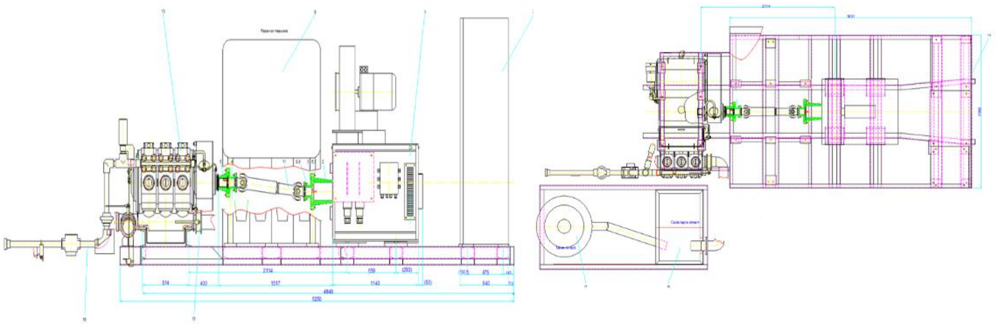


**Fig.1.** Installation for cementing and special operations

**Fig. 2.** The complete installation placed on the truck

The movement received from the transmission is transformed from rotational movement, in the translation movement of the plungers, through a transmission mechanism equipped with gear in "V".

The transmission mechanism is composed of:

- the gear in "V", which has the crowns fixed on the tree cranked by shepherd screws. The axial force developed in each crown pushes the crown to the shoulder of the crankshaft and does not create additional requests in the fixing screws. The direction of training of the pump will not change, in order not to change the meaning of the axial forces.

- the sprocket axis supported on 2 radial rollers that allow it to move the necessary axial to self -centered. The head of the pinion shaft is sealed with the oil bath with a sealing ring that works on a wear bush.

- the connecting rods have sliding camp, at the handle (bimetallic shell of two pieces) and at the head of the spherical joint.

- The head of a cylindrical cross is sliding into a shirt fixed in the body of the fream. Both the head of the cross and the shirt are made by casting, cast iron.

For normal operation between the cross and shirt head, a game of 0.180 - 0.230 mm is provided.

The circulation of fluids is ensured through the manifolds, which allow:

- the aspiration of the pump with plunging from each compartment of the measurement tank, from the fall aspiration for cement milk or from an external source, on both sides of the aggregate;

- reflation of the pump with plunging towards the mouth of the probe, on the barley in the measurement tank or outside. The refuse on the bar is achieved by an adjustable, manually commanded nozzle, which allows a slow and controlled pressure leak;

- feeding each compartment of the measurement tank from the exterior source as well as the independent emptying of each compartment;

- the aspiration of the water pump in each compartment of the measurement and discharge tank to the mixer through a system of water distribution towards the nozzles of the mixer and of recirculating the addition of aspiration.

The command of the aggregate are centralized and can be performed from the podest located around the control desk. At the control desk are mounted both the appliances of the operation of the pump and the water pump, as well as the necessary to follow the operation of the drive engine. In order to follow the discharge pressure, the aggregates are provided with medium insulator and shock absorber, mounted on the pump discharge collector, [1, 27].

### Pumps with plunging used in cementing, cracking equipment

Within this work, only the plunger pump within the cementation installation was studied this is a duplex / triplex pressure pump with simple effect, with

cylindrical gear in "V" built especially for the operating regime of the cementing aggregate.

The pumps are designed to operate in a reduced speed (35-200 double/minute races), ensuring a good filling of the pump cylinders and a volumetric efficiency over 0.9 to a natural aspiration without overload. This is a feature, useful because it simplifies the exploitation and increases the field of use of the cementing aggregate. Without diminishing the volumetric efficiency, the hydraulic part of the pump can be equipped, as needed, with Ø 90 mm, Ø100 mm, Ø 115 mm and Ø 125 mm. [1, 27].

The cementing aggregates are used in the preparation and pumping of the cement paste or suspensions (cementation operations), pumping the separation fluids and the discharge mud and other special operations (cracking, balancing).

In normal construction, the aggregates are mounted on self -chief, on semi -trailer, or rarely, in the case of marine drilling and isolated or removed locations, on the sleds provided with towing and lifting possibilities.

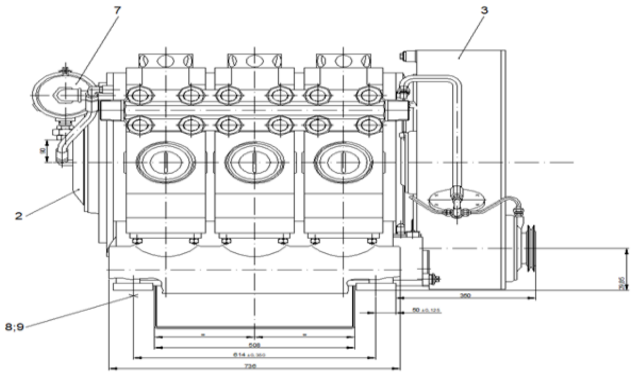
The self -important aggregates are made up of the following basic equipment: one or two pressure pumps with pluners or pistons, which provide normal technical parameters to natural aspiration; a toothed wheels pump for water supply of the mixer / mixing funnel; a measurement tank divided into two compartments equal to 100 liters grades, protected against corrosion; through it, filling and emptying the two compartments alternately, the volume of mud pumped in the probe is measured to place the paste in the desired space; cement mixer with nozzles (for cementation operation), powered by water by the water pump; the manifolds of the aggregate.

Based on the synthesis performed, the conditions that must be respected have been highlighted for the equipment to ensure the optimal operating parameters in order to successfully carry out the operation:

- the design of the aggregates takes into account the degree of use, taking into account a total number of hours for dimensioning bearings, gears or other organs, much lower than in machines with a continuous operating life and constant load. This hypothesis leads to the creation of component machines of the aggregate, as low as possible, an essential condition for a mobile pumping aggregate.
- it is also taken into account that for a certain flow and pressure, the dimensions of the pump, so its weight are determined by the length of the race and the speed of the crankshaft.
- designing the cementing /cracking operation also involves the selection and use of the most appropriate cracking fluids and support materials. The quantity of these components and the injection mode are essential for the success of the operation.
- the equipment must provide through their components and increased resistance to corrosion and abrasion, taking into account that the fluids involved in these operations have a strong corrosive and abrasive effect.

**Fig. 3** Triplex pump with plunger

a). The physical realization of the designed pump




b). Overall project

**Table 1**. Pumps with plunging use in cementing, cracking equipment

| Aggregate type / pump | Maximum turation at the input pump (rot./min) | Plunger/piston diameter, mm | | | |
|---|---|---|---|---|---|
| | | 100 | | 115 | |
| | | fluid flowl (l/min) | pressure, (bar) | fluid flowl (l/min) | pressure, (bar) |
| ACF 700 Triplex pump with plunging | 204 | 258 | 700 | 296 | 550 |
| | 485 | 412 | 470 | 472 | 350 |
| | 728 | 617 | 310 | 710 | 230 |
| | 971 | 823 | 230 | 945 | 170 |
| | 1457 | 1235 | 150 | 1419 | 120 |
| | 2100 | 1780 | 100 | 2047 | 80 |

**Trends regarding the materials used in the construction of equipment for special operations in wells**

The materials used in the construction of the components of the analyzed equipment, have a certain behavior under the attack of the corrosive and abrasive mixtures used in the special operations.

Martensitic stainless steels contain between 12-17 % CR and over 0.1 % carbon. The martensitic steels in a hardened and returned state have a good resistance to corrosion in environments containing nitric acid, carbonates, sulphates. These steels are recommended for the manufacture of elements subject to wear in corrosive environments. The treatment applied should not lead to the separation of chromium carbes, [28]. Reducing the content in chromium below 12 % in certain areas will cause local corrosion. Table 2 presented the main fields of their use.

**Table 2.** Areas of use of martensitic stainless steel steels

| Steel brand | SR EN 10088-1 | Applications |
|---|---|---|
| 35MoCr165 | 1.4122 | Elements that work in water, steam, weak solutions of organic or inorganic acids, subjected to wear by adhesion or erosion, at low temperatures |
| 90VMoCr180 | 1.4112 | Wear -resistant elements in corrosive environments |
| 8Cr170 | 1.4016 | Elements that work in medium aggression environments |

**Table 3.** Composition of commercial packages of inhibitors

| Packages of inhibitors | The quantities of corrosion inhibitors |
|---|---|
| A | 37.85m3 (10 gpt) corrosion inhibitor I and 13.6 kg (30 ppt) reinforcement inhibitor E |
| B | 75.7 kg (20 gpt) corrosion inhibitor II, 9 kg (20 ppt) reinforcement inhibitor E and 227 kg (60 gpt) reinforcement inhibitor F |
| C | 37.85-75.7 kg (10-20 gpt) corrosion inhibitor I and 37-75 kg (10-20 gpt) reinforcement inhibitor G |
| D | 45-55 kg (12-15 gpt) corrosion inhibitor III and 12-15 gpt reinforcement inhibitor H |

Note: gpt = 3.785 m3 corrosion inhibitor to 3785 m3 acid
ppt = 0.4536 kg corrosion inhibitor to 3785 m3 of acid

Each steel sample was previously cleaned by blasting glass balls in order to remove impurities. The samples were weighed before and after testing to determine the weight loss losses. The samples were tested for 6 hours. After testing the samples were cleaned with acetone and slightly farimity to remove the residues of corrosion inhibitors or the film formed during testing. The samples were examined for the evaluation of microscope pitting. The evaluation of the loss of material by corrosion is based on comparison with the level accepted in the industry up to 0.2 kg of corroded material at an area of one square meter [16].

In addition, the evaluation of pitting is made according to the scale presented below. On the pitting scale a value greater than or equal to 2 is considered unacceptable in the case of acidization treatments, even if the loss of corrosion material is within acceptable limits.

**Table 4.** Pitting scale evaluation

| Pitting scale | Interpretation / observations | Pitting scale | Interpretation / observations |
|---|---|---|---|
| 0 | no hole on the surface | 3 | small holes with sizes (1/32 in) 0.79 x$10^{-3}$ m to (1/16 in) 1.5 x$10^{-3}$ m |
| 0-1 | some small shadows on the metal surface | 4 | average holes smaller than (1/16 in) 1.5 x$10^{-3}$ m |
| 1 | small shadows on the surface | 5 | large, deep holes all over the surface |
| 2 | small dots on the surface | | |

Results obtained from the use of different combinations of acids [32]. Through the experiments done it has been shown that when the 13CR steels are exposed to the action of the acidization fluids, depending on the packages of inhibitors used, their behavior in corrosion is completely different.

The recorded results highlighted the following conclusions:

- 5% HCL + 10% acetic acid - the A and B inhibitors packages have failed to protect the steel on corrosion. Even given the concentration of the inhibitor I was 100% no changes in CE2-13CR steels. In the EC1-13CR steel a double amount of inhibitor and increased performances by 38 %, but the loss of material by corrosion remained far beyond the accepted values.

-10% HCl The packages of inhibitors provided protection at the R1-13CR steel and the CE2-13CR steel.

- 15% HCl. By using the inhibitor package C, both 13CR and high ally steel protection has been achieved.

The use of package D provided protection for both the discussed and combination case, 5% HCL + 10% acetic acid. In the presence of inhibitors it can be said that the influence of mechanical properties on corrosion behavior can be ignored, and the loss of material by corrosion is included in standard values.

- 9% HCl +1% HF. The inhibitory package C effectively protects CE1-13CR and CE2-13CR steels. In the other cases the protection failed.

**The technologies of specific treatments applicable to the materials from which the complaints are executed in order to increase the durability**

Regarding the plungers, at the moment the materials are commonly used: OLC 45, 18MNCR11 (18MNCR10) it is an ally for hot processing.

Nitruration is a thermochemical treatment that consists in the enrichment of nitrogen of the superficial layers, in order to improve some surface characteristics, such as hardness, wear resistance, resistance to grip, bending by shock, etc.

In the presence of nitrogen, iron alloys form nitrous and iron carboniters, at low temperatures, which have a hardness and resistance to very high wear. Nitrogen, forms nitrous, finely dispersed, with iron (Fe) and the elements of the Fe, especially aluminum (Al), chrome (CR), vanadium (V). Thus, the following nitrous can be formed [37]. The nitride is done at low temperatures, between 500-580ºC. This avoids the diffusion of nitrogen in the core and the coalescence of the nitrics. It results, a depth of low nitride (usually 0.2-0.6 mm). [36].

Within the present work, the ionic nitrier process is used is based on the principle of luminescent discharge in a rarefied atmosphere. The pieces are arranged at the cathode of a retort, the anode representing the walls of the retort. Between the cathode and the anode there is a light discharge, and a voltage drop that leads to plasma formation is performed. The ions of H and N bombard the piece, producing the increase of the temperature up to 400 - 500 °C and the removal of the Fe atoms.

They form with ions in the iron nitros that are deposited on the piece. The processing duration is reduced (8-12 h), and the quality of the nitrus layer is superior, because it is formed, especially, the phase $\gamma'$. The presence of carbon provides characteristics superior to the nitrus layer by forming Fe3 (C-N) nitri, which is why it is recommended to submit to the nitrurization of the improvement steels (in a state of high quality and return) with a content of 0.4 - 0.7 % C.

A fundamental element of the new innovative solutions is the materials used and the specific treatment technologies applicable to the surfaces of the plungers, the mixing bowl, the manifolds and the screws. In this sense, the trends regarding the materials needed to be used and new technologies, such as nitrating, were studied, with possibilities to determine the quality of the coating in the Company PETAL laboratory.

The identification of innovative methods to optimize the plunger pump was initially developed in the analysis of the sealing system. Based on the results from the specialized literature obtained through modeling and simulations, important conclusions were obtained regarding the constructive form and material of the gaskets, and a new, improved form is proposed for the sealing package as well as for the materials from which it is made.

Triplex pumps are specially built for the operating regime of cementing/cracking aggregates and have the following composition: hydraulic part, hydraulic body, valves, suction manifold, plunger-jacket assembly which are subject to the action of physical and chemical corrosion and abrasion, these are amplified by the thermal effect caused by the friction of the materials involved in the pumping process based on the analysis of the operating conditions of the cracking equipment, the following degradation mechanisms are highlighted:

- if the cementing process involves cement mixtures, additives, considering their abrasive/corrosive nature, the parts and subassemblies that make up the high-pressure pumping system will be exposed to abrasive and corrosive action;
- if the cracking process involves sand-based mixtures, considering its abrasive nature, the transport elements of the sand and additives will be exposed to the action of abrasion wear;
- if the cracking process involves acidification, the parts and subassemblies that make up the high-pressure pumping system are exposed to a strong corrosive action.

To reduce the effects of corrosion, the use of special technologies for covering the plungers, which are tubular in shape and are hard chromed on the outside, the use of stainless steels based on Cr, Ni, especially at the manifolds of the transport system, the use of corrosion inhibitors, alternative chemical treatments, plating dishes with high-density polyethylene.

## Results and discussion

### Modeling and simulation in Solidworks for the components of the innovative cementing plant and special well operations

A new constructive solution is analyzed and proposed for plunger valves based on conclusions obtained from the theoretical modeling study. For plungers, the analysis indicates the need to use some deposited materials for the substrate and layer, and the technologies of thermal spraying and metallization of the surfaces subject to wear are indicated.

The study dedicated to solutions in the field of introduction of asynchronous motor drive contains elements related to the electric drive components:

- the study of the electric actuation solution;
- the characteristics of the asynchronous motor dedicated to the drive and the establishment of the technical specifications necessary for the design of the drive solution;
- analysis of the static frequency converters that can be used in the engine control respecting the characteristics of the driven pumps;
- solutions of electrical actuation schemes usable for the actuation of the cementing plant for oil wells.

### Materials used and treatments applied

Metal steel plungers are ideal for applications that require resistance to abrasion, vibration, thermal shock and impact, as well as high mechanical strength.

According to API 674 edition 3 - 2010 art 6.7.2.1, the surface of the metal plunger in contact with the sealing package / gasket set must be hardened or covered. The surface of the plunger in contact with the sealing package must have at least a Rockwell hardness of 35 on the C scale. The surface must be processed so that it has a roughness of Ra < 0.4 μm.

Usually, the metal plungers used in the petroleum field are made in tubular form from alloy steels, such as OLC45 (quality steel with 0.45% C) and 18MnCr11/18MnCr10 (alloy steel for hot processing), which in the classic version are plated on the outside with a hard layer of chrome to increase resistance to wear and corrosion.

Although the solution of plating steel metal surfaces with a hard layer of chromium (VI) for protection against wear and corrosion is a technically viable solution, however, there are elements of risk to the health of operators and the environment due to the toxicity of chromium hexavalent - Cr (VI), which is used during processing. For this reason, worldwide, there have been research and development concerns for new, alternative and ecological solutions since the beginning of the 1990, solutions that are still being developed. Currently there are massive restrictions on the use of processes that lead to Cr (VI) emissions, such as those resulting from plating with a hard chromium layer. One of the procedures for increasing the durability of the plunger surface, which has seen extensive research and development in recent years, is thermal spraying [65].

Thermal spray depositions and thermochemical surface treatments are excellent and viable alternatives to use in place of the hard chrome plating method. In addition to the environmental reasons for using these alternative processes, they offer other advantages such as improved long-term performance: coatings with improved wear behavior, good corrosion resistance, low repair costs and maintenance, optimal level of residual stresses, with significantly improved fatigue behavior, increased lifetime, lower cost prices.

**Finite element simulation of the heat transfer inside the triplex pump with plunger**

The thermal effect caused by the friction of the materials involved in the pumping process of the main parts of the pump component that are subject to the action of physical and chemical corrosion and abrasion was analyzed we have made finite element simulations, using the Solidworks and LISA 8.0.0 software, Figure 4.

Finite element analysis of the thermal stress and demands of plunger pump was performed using specialized software for finite element analysis using the one preprocessor.

The main steps of finite element analysis software are:

a). pattern preprocessing part plunger pump modeling and preprocessing model and creating finite element structure, determine the properties of the material of the piece Figure 5;

b). Processing piece finite element model (FEM).

- establishing the conditions for contour surfaces and values imposed restrictions;

- solving the finite element method (FEM) and display the results for thermal analysis.

Finite element analysis results are presented in the whole volume of the piece and representative sections for drawing conclusions on the analyzed part identifies the most dangerous sections following that on them to carry out thorough investigations.

**Fig. 4.** Triplex pump with plunger

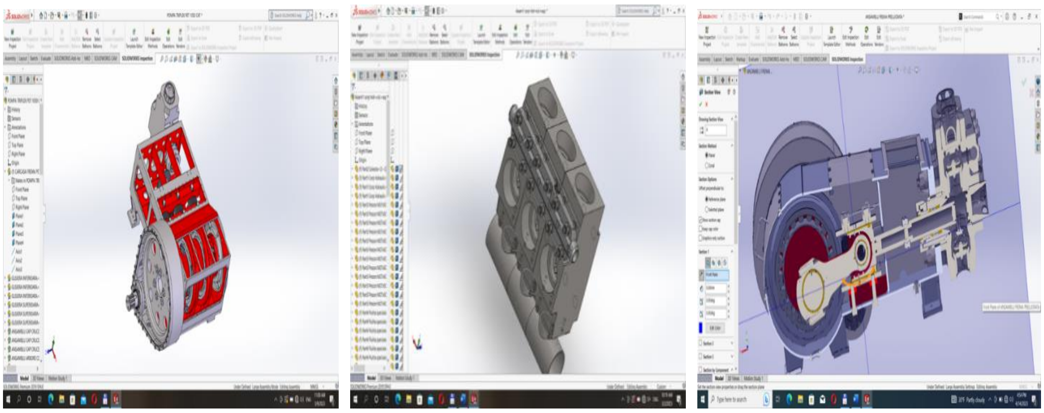
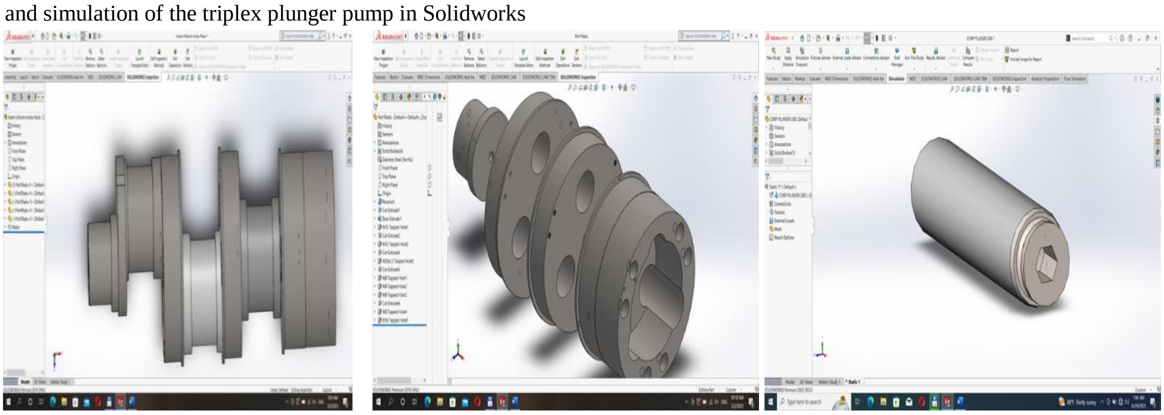
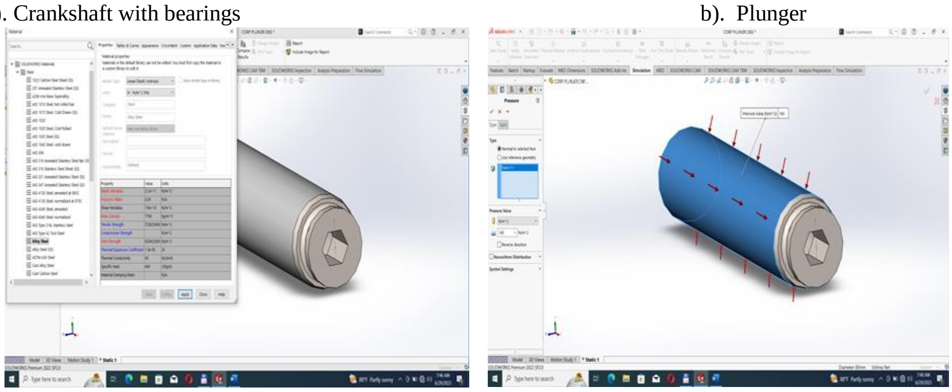


**Fig. 5.** Modeling and simulation of the triplex plunger pump in Solidworks

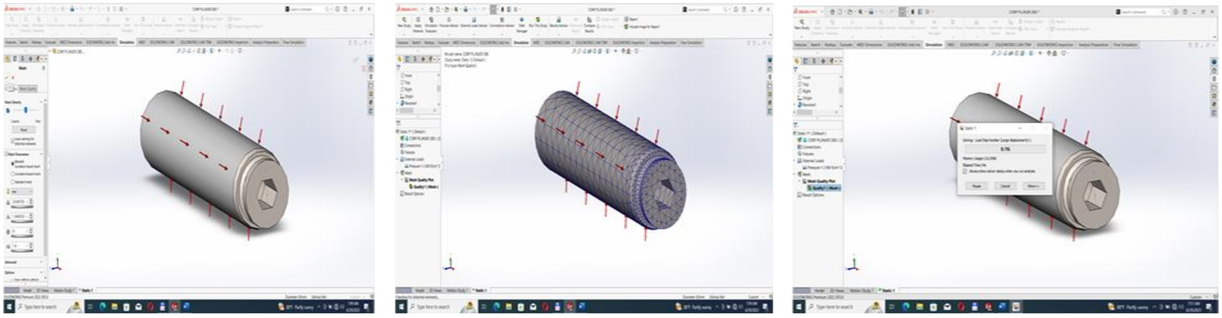


a). Crankshaft with bearings b). Plunger

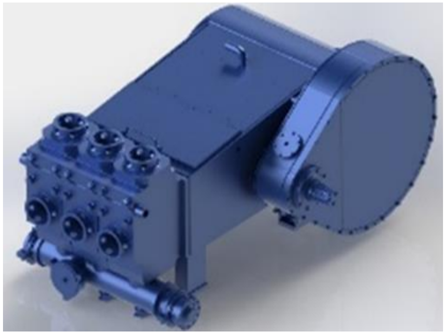
**Fig. 6.** The design and simulation in Solidworks of the components affected by wear due to the thermal effect of the fluids in the triplex plunger pump



a). The finite element mesh and the boundary conditions

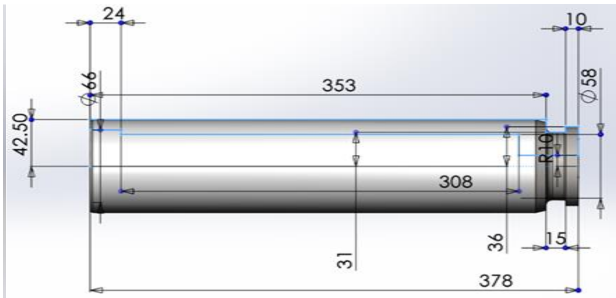


b). running the simulation

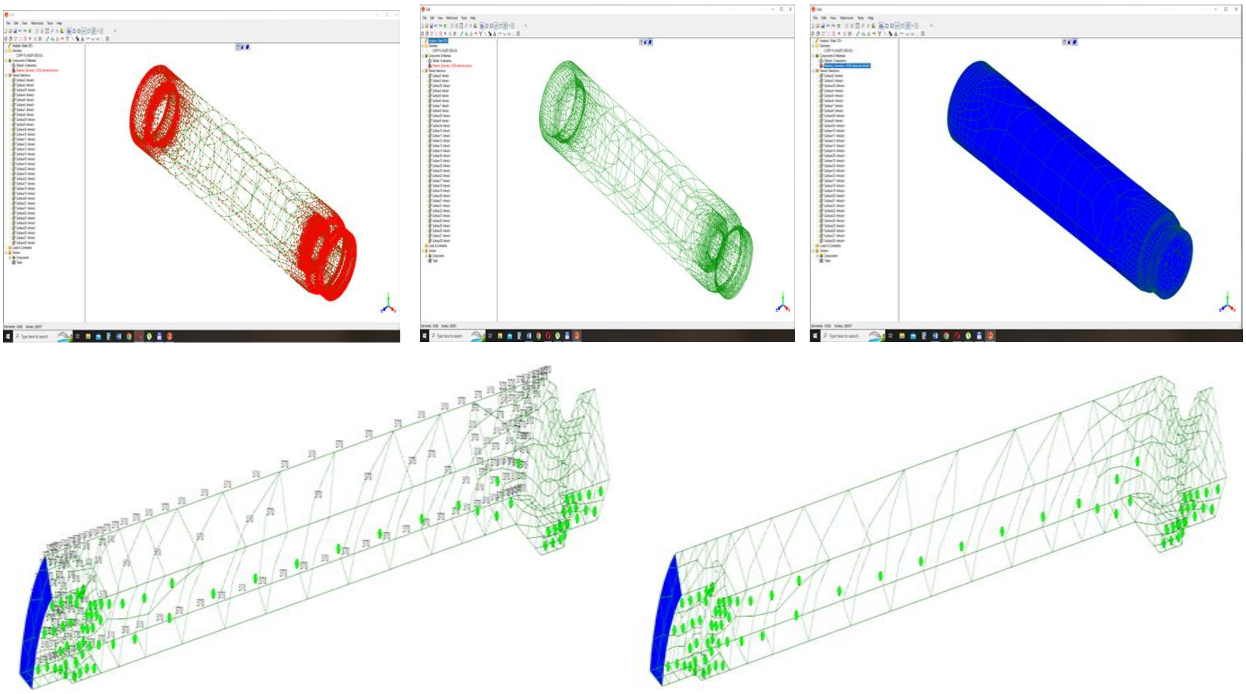


c) the result of simulation

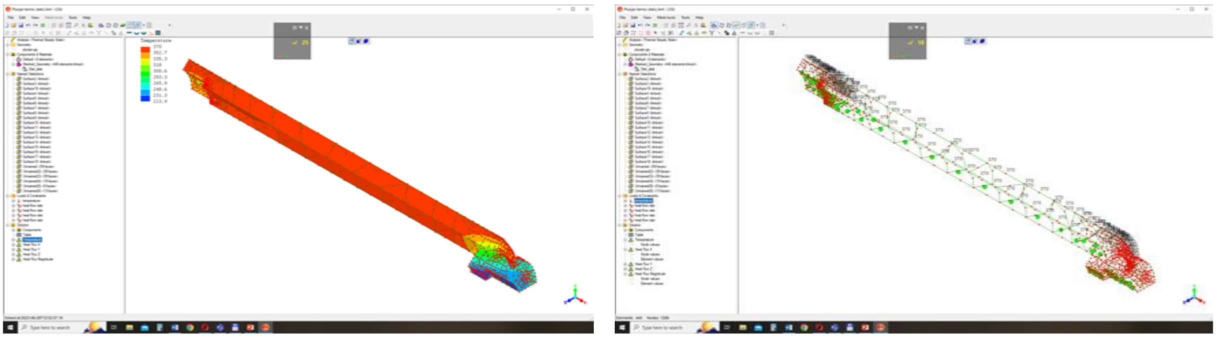
**Fig. 7.** LISA v 8.0 finite element simulation of the plunger



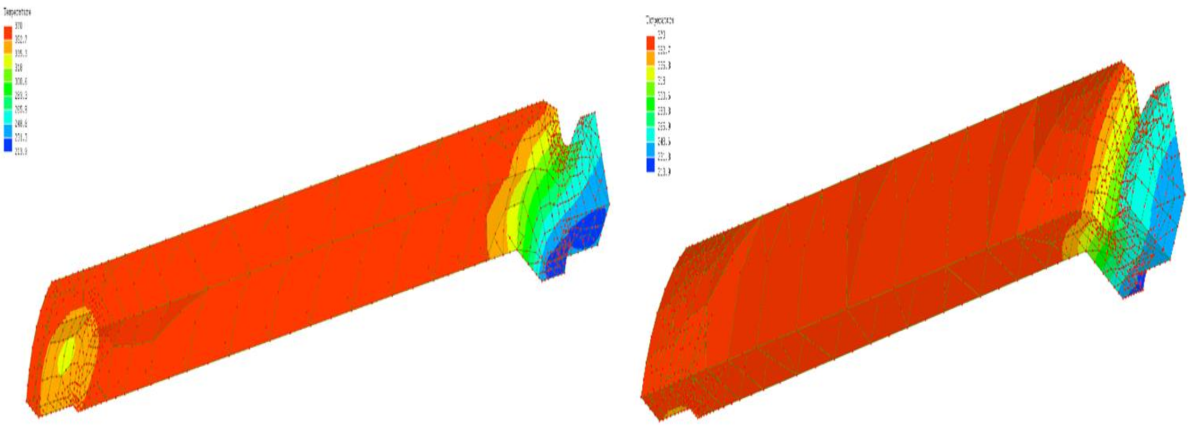

a). Plunger pump and plunger execution drawing



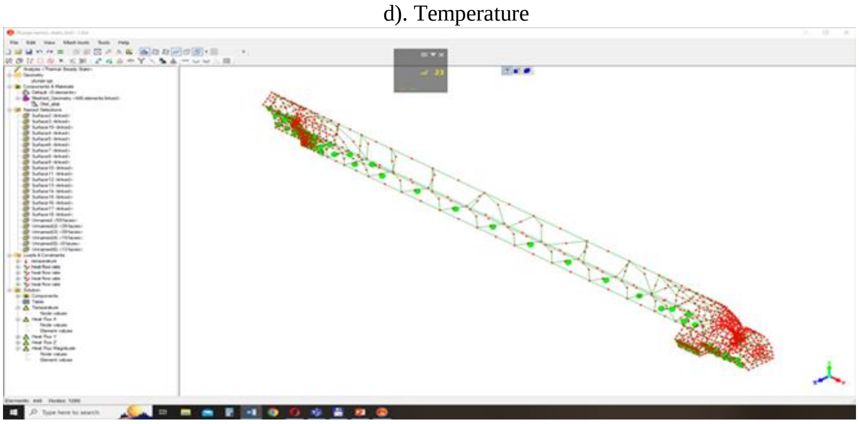
b). discretization and imposition of boundary conditions for the plunger



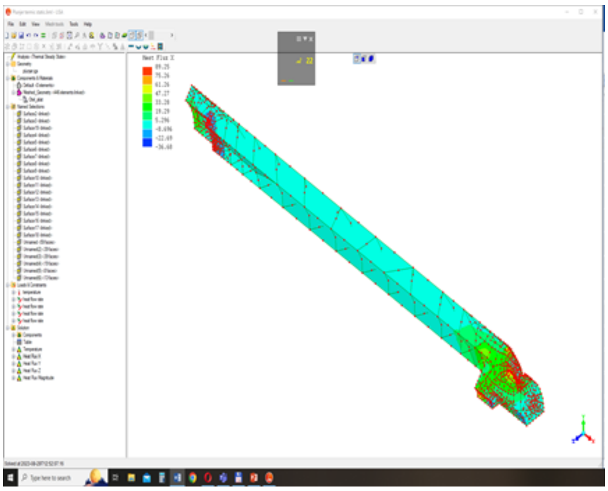
c). thermal analysis for a significant volume of the plunger



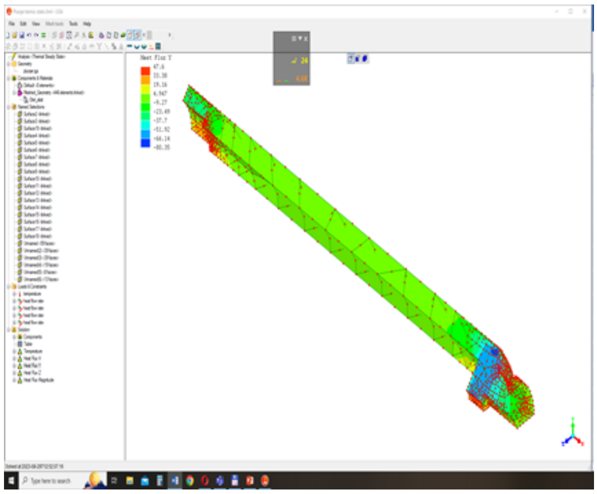
d). Temperature



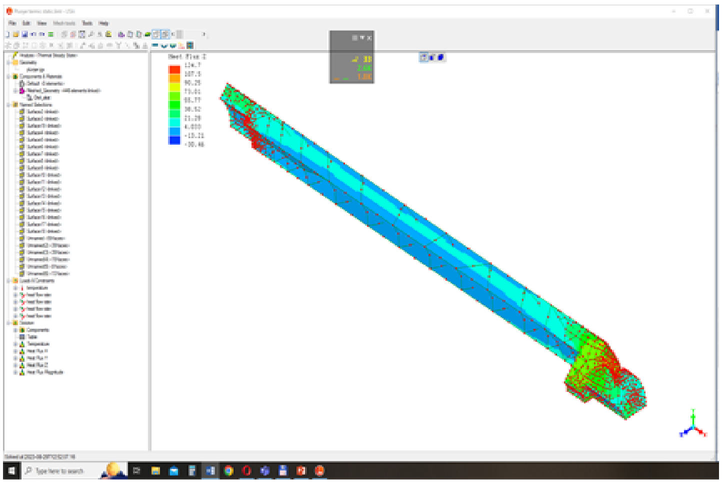
e). Heat flow rate



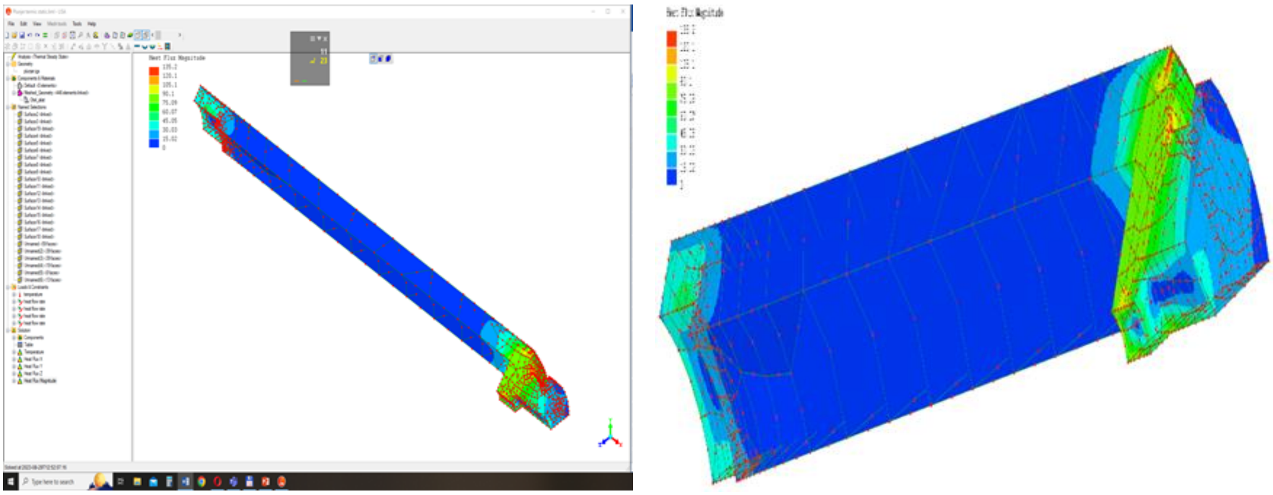
f). heat flow along the X axis



g). heat flow along the Y axis



h). heat flow along the Z axis



j). Heat flux magnitude

**High resistance thermal spraying using forced combustion of oxygen – the HVOF (High Velocity Oxygen Fuel) process**

For the experiments, surface coatings with Mo were made by the three methods on samples of different shapes and sizes adapted to the techniques, methods and standards of analysis or testing applied. For the realization of the preliminary experimental variants of surface coverings, the A5T steel (42CrMo4) currently used for the realization of the drive axles of the metro trains was selected as the support material. Alternatively, a steel with superior properties (34CrNiMo6) was considered for the realization and testing of the optimal molybdenum metallization options. The two types of steel used, Table 5. were in the form of Ø 30 mm rolled bars in annealed condition.

For the preparation of the support materials, it was aimed to determine the optimal thermal treatment conditions for obtaining the mechanical characteristics imposed on the steel from which the tubular axles of the subway trains are made, starting from the premise that after the reconstruction by metallization of the mounting surfaces of the mounted axle, there should be no influences on service requests or projected loads. From this perspective, the experiments to prepare the support materials were focused only on determining the heat treatment conditions that would ensure the designed mechanical properties.

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**Table 5.** Chemical composition (% mass) of the steels selected for experiments [73]

| EN 10083 | W. Nr. | C | Si | Mn | P | S | Cr | Mo | Ni |
|---|---|---|---|---|---|---|---|---|---|
| 42CrMo4 | 1.7225 | 0,38-0,45 | < 0,40 | 0,60-0,90 | < 0,035 | < 0,035 | 0,90-1,20 | 0,15-0,30 | - |
| 34CrNiMo6 | 1.6582 | 0,30-0,38 | < 0,40 | 0,50-0,80 | < 0,035 | < 0,035 | 1,30-1,70 | 0,15-0,30 | 1,30-1,70 |

In order to evaluate the metallized layers, the following morpho-structural and mechanical characteristics were investigated, considered to be essential for validating the optimal solution of surface coatings for the protection and dimensional reconstruction of the components:

- microstructural characterization by analyzing and processing SEM images (surface and cross-sectional microstructural characteristics, porosity, substrate-coating adhesion/coating layers, thicknesses and diameters of splats, cracks, inclusions, etc.);
- topographic characterization of the coatings (roughness determined by mechanical palpation, 1D and 2D roughness determined based on three-dimensional images - stereo images);
- vickers microhardness measurements;
- determination of the modulus of elasticity;
- determination of the breaking toughness of the coatings;
- determination of adhesion resistance on raw and rectified surfaces with thicknesses of the metallized layer in the range of 100 - 600 μm;

The results obtained during the experiments highlighted: the investigated Mo metallized layers present particular microstructural characteristics determined by the thermal spraying methods used, characterized by successive layers of flattened particles, scattered upon impact with the substrate, with porosities, cracks and oxidized particles.

Although all three methods result in metallized layers with a similar anisotropic structure, the flattened particle sizes are inversely proportional to the impact energy determined by the thermal spraying method: at high impact energies (HVOF) smaller flattened particle sizes result (Daverage = 37 μm), compared to the APS method (Dmean = 93 μm) and electric arc (Dmean = 138 μm).

The same tendency was determined for the thickness of the flattened particles (h) and the degree of deformation of the particles (ξ).

A direct correlation was determined between the sizes of the flattened particles and certain intrinsic properties of the metallized layers: in the case of smaller sizes (HVOF), more compact and denser coatings result, with higher tenacity, with a level of internal porosity and a higher surface roughness reduced, compared to the coatings obtained by electric arc or plasma jet.

Although metallization by APS produces flattened particles of smaller sizes, coating layers with greater compactness and a lower level of porosity than in the case of the electric arc metallization method, the difference of approx. 1% regarding the determined value of the density (8.86 g/cm3 for APS and 8.97 g/cm3 for AE) can be associated with a higher content of oxidized particles in the coating layer.

The much higher spraying temperature in the case of the APS process generates a higher content of Mo oxides which have a much lower density than pure Mo. As a general finding, in the case of layers deposited by thermal spraying by different methods, the presence at the microstructural level of oxide inclusions, pores and discontinuities that generate different levels of compactness, the determined values of the density are lower than those of the pure metal from which originate

Determining the fracture toughness by microindentation of the investigated metallized layers showed a tendency to increase the fracture toughness values depending on the indentation load, in both indentation directions (parallel and perpendicular to the interface with the substrate), for all three types of coatings of molybdenum.

The evaluation of the usage properties of the molybdenum coatings, adhesion resistance and tribological properties, revealed the fact that larger sizes of the flattened particles obtained by electric arc spraying determine a better behavior of the metallized layers.

In order to evaluate the specific rate of wear for the layers metallized with Mo by the three thermal spraying methods used, additional micro-abrasive wear tests were carried out for the same friction duration of 900 sec. corresponding to the transition point between the break-in period and the stable wear period, previously determined. For comparison, a set of determinations was also performed on 34CRNiMo6 steel samples; 42MoCr4 unmetallized.

The experimental results indicate that the specific rate of wear for samples metallized with Mo by electric arc is lower than in the case of metallization by APS.

**Fig. 8.** Procedeu de depunere HVAF prin pulverizare a carburii de wolfram pe un plunger de pompa [76]

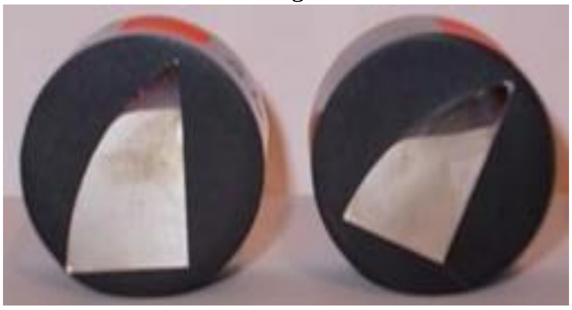
**Analysis of samples of heat treated parts by electron microscopy SEM and EDAX spectrometry**

For the tests and experimental measurements were used samples of plunger made of steel C45-RO1.0503
Micro structural analysis of plunger, was performed on a scanning electron microscope VegaTescan LMH II of pearlite grains are coarse classic uniformly distributed in the ferrite matrix therefore blade material's mechanical

**Fig. 9.** The test pieces taken from heat-treated

SEM, working - 46 High using detector type LFD (Large Field Detector), acceleration voltage electron beam used was 30 kV, and working distance was 15 mm. From the analysis of samples by electron microscopy SEM shows that if the heat treatment

properties are reduced, the piece has a reduced durability and low mechanical strength.



EDAX analysis was performed on the sample surface layer to highlight its chemical composition is observed the presence of chemical elements Fe, C, Mn, S, Si and $O_2$ in different proportions corresponding to the chemical composition of steel C45-RO1.0503. Determination of chemical composition of the material for plunger EDAX spectrometry was performed on a scanning microscope SEM electrons VegaTescan LMH II concentrations determined by mass spectrometry EDAX elements of sample material taken from the plunger specified in table 6. Bruker Quantax AXS Microanalysis GmbH, Germany

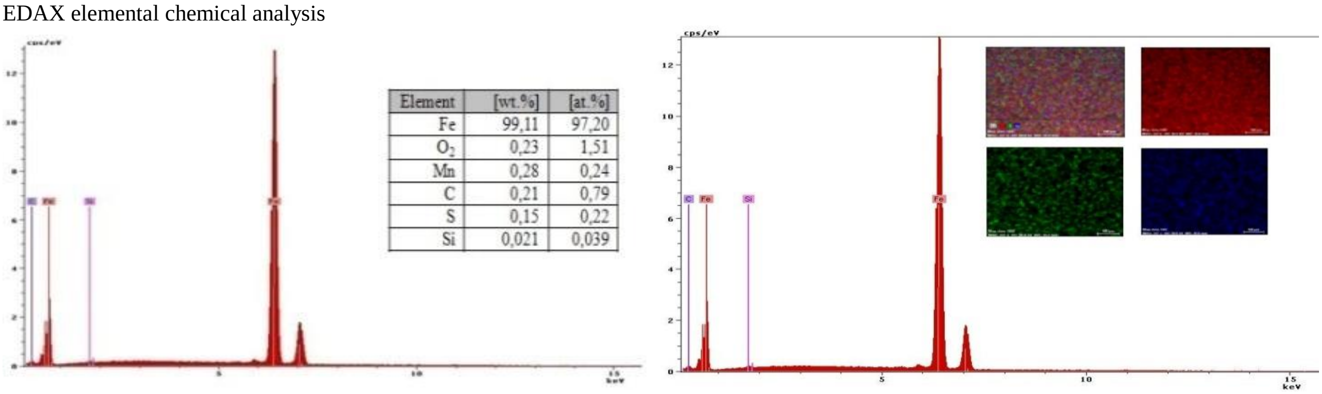
Results Acquisition 4588 Date: 26/09/2023

**Table 6** Chemical composition of the material sample in percent by mass.

| Element | AN | Net | [norm. wt.%] | [norm. at.%] | Error in % |
|---|---|---|---|---|---|
| Iron | 26 | 145203 | 99,106 | 97,202 | 2,54 |
| Oxygen | 8 | 3832 | 0,227 | 1,508 | 1,02 |
| Manganese | 25 | 5935 | 0,284 | 0,237 | 0,14 |
| Carbon | 6 | 1756 | 0,208 | 0,795 | 0,48 |
| Sulfur | 16 | 2605 | 0,154 | 0,219 | 0,10 |
| Silicon | 14 | 206 | 0,021 | 0,039 | 0,05 |
| | | Sum: | 100 | 100 | |

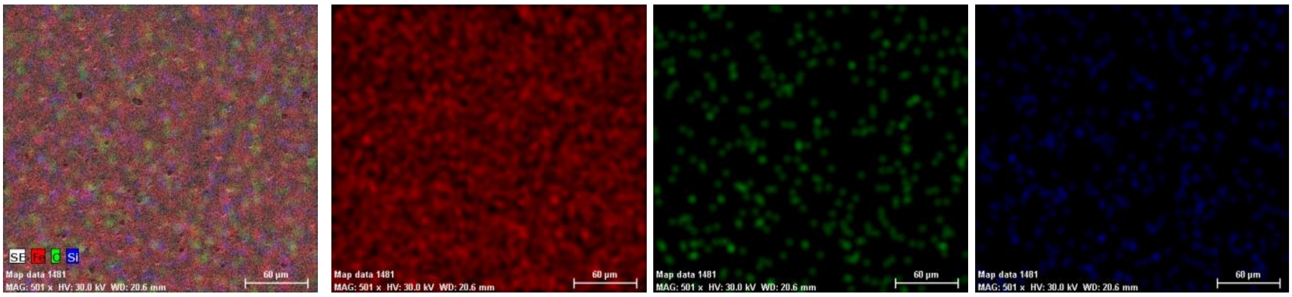
In samples from the furnace heat treated plunger management system based on a step predictive algorithm is found that iron is observed following elemental analysis is found uniformly distributed in the base material as can be seen in the distribution map. The oxygen is uniformly distributed in the base material at many generally it is in the form of oxides. Carbon is present in the iron alloy, uniformly distributed, but is observed uniformly dispersed islands alloys thereof chemical compounds with Mn, S and Si. Manganese is contained in the form of islands uniformly dispersed large mass of the base material.
Sulfur is a small scale and appears in different alloys with Fe, Mn, C, uniformly dispersed in the base material.
Silicon is insignificant and appears only as an alloying element to the base material.
Chemical and elemental analysis, samples taken from plunger, heat treated in a furnace that has implemented a management system structure predictive control algorithm based on a step is shown in Figures 10 and 11.

**Fig. 10** Map of the distribution of chemical elements for the piece EDAX elemental chemical analysis a) SEM image b) EDAX elemental chemical analysis



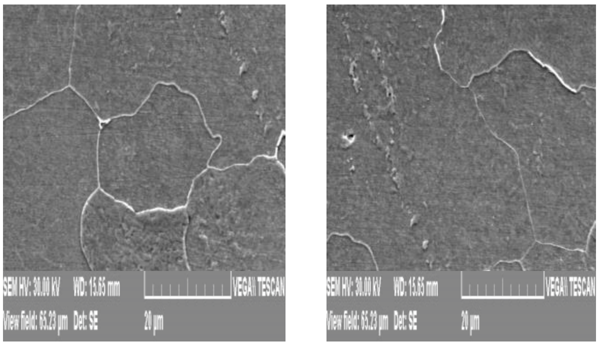
Microstructures analysis of low power plunger made of steel C45-RO1.0503, performed on a scanning microscope SEM electrons VegaTescan LMH II are shown in the following figure.
Name of sample material: steel C45-RO1.0503
Chemical composition: C = 0.49%; Mn = 0.24%; Si = 0.039%; S = 0.22%
Scanning electron microscopy (SEM)
Length bar: 20 μm
Description: carbon steel microstructure - ferrite and pearlite grains distributed in plunger.

**Fig. 11.** Map of the distribution of chemical elements for the piece heat treated



all elements map Fe map C map Si map

**Fig. 12.** SEM image of pale material heat treated in heat treatment furnace temperature sensitive thermostatic controlled with a PID one step ahead controller



*a) micrographs M1* *b) micrographs M2*

From the analysis of samples by electron microscopy SEM shows that if the heat treatment of pearlite grains are coarse classic uniformly distributed in the ferrite matrix therefore plunger material's mechanical properties are reduced, the plunger has a good running low, low durability and low mechanical strength.
We mention that there is an compliance reliably between hardness and mechanical characteristics and plasticity of the plunger so resistance high hardness and a uniform distribution of microcrystalline phases (ferrite and pearlite) ensures high durability and toughness to play a positive effect on time to good works plunger simultaneously increasing the capacity of taking hydraulic shock due to fluid flow in pump, also increases resistance to corrosion and cavitations wear the plunger.
The experimental results are taken from data acquisition board installed in the control system of electric furnace for heat-sensitive treatments. The chemical, physical, mechanical and structural were highlighted by experimental laboratory determinations were performed on standard test specimens, specific tests.
Determination of chemical composition by EDAX spectrometry allowed a comparative analysis of the distribution of chemical elements in samples of material palettes microcell reveals the fact that if the heat-treatment furnace control system based on predictive algorithm on a step more uniform dispersion of chemical elements is relatively samples heat treated in an furnace with PID control system that enables the conversion of a greater percentage of austenite pearlite dispersed to obtain uniform fine structure that leads to an improvement of the mechanical properties of the part.
From the analysis of samples by electron microscopy SEM shows that if the heat treatment of pearlite grains are coarse classic uniformly distributed in the ferrite matrix therefore plunger materials mechanical properties are reduced, the plunger has a good running, low durability and low mechanical strength.
If the heat treatment temperature sensitive heat treatment furnace realized ordered thermostatic control systems with PID one step ahead structure of the material consists of fine pearlite crystalline grains uniformly distributed in the ferrite matrix, the mechanical properties are superior parts have a resistance high mechanical wear and high toughness.

## Conclusions

The carrying out of cementing and cracking operations at the oil well requires specific conditions that require the establishment, on a scientific basis, of the criteria for the selection and efficient use of the related equipment, the equipment/aggregates are characterized by the maximum pressure, this parameter being also a coding index. In principle, aggregates with pressures up to 700 bar are intended for cementing operations, those with pressures greater than 700 bar are also intended for cracking operations.

The operating time of the cementing or fracturing aggregate is much lower, compared to that of the drilling machines, being estimated at approximately 1500 hours annually. Of this working time, the operation of the aggregate at maximum parameters represents a fraction of the order of 20-30%.

The equipment must ensure the optimal operating parameters in order to carry out the operation successfully, the design of aggregates takes into account the degree of use, taking into account a total number of hours for the dimensioning of bearings, gears or other organs, much less than for machines with a continuous operating time and constant load. This hypothesis leads to the creation of equipment components of the aggregate, with as little weight as possible, an essential condition for a mobile pumping aggregate.

It is also taken into account that for a certain flow rate and pressure, the dimensions of the pump, and therefore its weight, are determined by the length of the stroke and the speed of the crankshaft.

- the design of the cementing/fracturing operation also involves the selection and use of the most appropriate fracturing fluids and support materials. The quantity of these components and the way of injection are essential for the success of the operation.
- the equipment must ensure, through their components, an increased resistance to corrosion and abrasion, taking into account the fact that the fluids involved in these operations have a strong corrosive and abrasive effect.

Within the work, the materials used and the coating techniques with corrosion and wear -resistant layers are approached to increase the durability of the plunger, key element in the functioning of the pump with high pressure. A large analysis of the thermal spray procedures used in recent years with very good results in the practice of the execution of the complaint has been performed. They were identified and selected as representative: thermal spraying / metallization with flame (fuel) high -speed (HVOF) and high resistance thermal spray using a lower oxygen concentration - HVAF. All the components of the equipment for which innovative solutions and integrated novelty elements were presented were presented, so for the triplex pump with plunging: they were studied:

- various constructive variants for the sealing package of the plunger, integrated according to the conditions that will be established in the design stage (working pressures)
- Constructive solutions for Plunger, integrated according to the conditions that will be established in the design stage
- treatments for the protection of metal complaints against corrosion and wear;
- Treatments to increase the durability of the plunger surface by depositing under plasma jet
- The use of modern materials identified in the study for plunging considering the behavior of the substrate material for different applicable treatments.

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**Author contributions**

All authors contributed equally to the realization of the scientific article.

**Data availability** Data will be made available on request.

## Declarations

**Conflict of interest** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## References

1 Adam A., Composite layered material - Invention patent " No. 119 604 B, 28.02. 2000;

2 Alok Satapathy, - Thermal spray Coating of Red Mud on metals, Department of Mechanical Engineering National Institute of Technology Rourkela, India, November, 2005;

3 Anton Paar GmbH, Viscosity of Crude Oil, 2020, https://wiki.anton-paar.com/en/crude-oil/

4 Atanasiu, V., A. Purcel - Oil extraction practice - Technical Ed 1971;

5 Brinke T., Plasma-Assisted Nitriding Offers Production Flexibility, Industrial Heating, May 2001, https://www.industrialheating.com/articles/84271-plasma-assisted-nitriding-offers-production-flexibility

6 Brooks, B.E., Beckermann, C., 2013. Prediction of Heat Treatment Distortion of Cast Steel C-Rings, in Proceedings of the 61st SFSA Technical and Operating Conference, Paper No. 4.5, Steel Founders Society of America, Chicago, IL, pp. 1-30.

7 Byrne JH, Yang CFM. Plunger packing with wedge seal having extrusion recess. WIPO Patent No. 2012083179; 2012.

8 Carfi G.R., P.G. Cirimello, A. Cabo, Plunger with ion nitriding treatment for a hydraulic fracturing pump and a method for making said plunger, United States Patent Application US 2017/0082194 A1, March 17, 2017, https://www.freepatentsonline.com/y2017 /0082194.html

9 Carlone, P., Palazzo, G. S., 2011. Development and Validation of a Thermo-Mechanical Finite Element Model of the Steel Quenching Process Including Solid-Solid Phase Changes, Int. Apag.l. Mech. 46, pp. 955-971.

10 Chen X, Hao M. Development and application of PTFE graphite composite castings. Fluid Mach 2001;7:8–10.

11 Chi M. Analysis and countermeasures of high-pressure plunger injection pump seal. Pump Technol 2003;5:38–40.

12 Chuanxian, H. Bingtang , L. Huiling, 1984, Thin Solid Film, v 118, ;

13 Cinco, Ley, F. Samaniego, Transient Pressure Analysis for Fractured Wheels, JPT, 1749-1766 – September 1981;

14 Coloja, M.P., C. Popescu, Extraction of crude oil and associated gases - Technical Ed., Bucharest 1993;

15 Cristescu M., Oil extraction. Stimulation operations, intervention and repairs, Publishing House of the Petrol-Gaze University of Ploiesti, 2009, ISBN 978-973-719-298-1, https://www.academia.edu/13505942/Dictionar_de_petrol_interventii

16 Dawson, J., Pipeline Corrosion Management, PII Limited, United Kindom;

17 Dorman, J., F. Udvary, Comparative Evaluation of Temporary Blocking Fluid Systems for Controlling Fluid Loss Through Perforations, SPE Paper No. 31081, presented at the 1996 SPE International Symposium on Formation Damage Control, 14-15 February 1996, Lafayette, LA;

18 Economides M.J., Mc. Lennan, J.D. Brown, Roegiers, Performance and Stimulation of Horizontal Wells - Part 1, World Oil, June 1989, Part 2 World Oil, July 1989;

19 Economides M.J., Hydraulic Fracturing for Well Stimulation - 3rd ed. Wiley New York, 1991, End; Petroleum 4 (2018);

20 Fink J.- Petroleum Engineer's Guide to Oil Field Chemicals and Fluids, Elsevier 2012;

21 Gilstad BC, Gilstad DW. Plunger seal ring. U.S. Patent No. 8,276,918; 2012.

22 Heiman R.B., 'Plasma Spray Coating, Principle and Application', VCH, Weinheim, Germany, 1996

23 Herbert H. Tackett Jr., James A. Cripe, Gary Dyson, Positive displacement reciprocating pump fundamentals – power and direct acting types, Proceedings of the twenty-fourth International Pump Users Symposium, Houston Texas, 2008;

24 Hojmrle K. and M. Dorfman, 1985, Mod. Dev. Powder. Met., v 15(15),;

25 Hubbert M.K, D.G. Willis, Mechanics of Hydraulic Fracturing, Trans. AIME 210 , 152 – 168 , 1957;

26 Johnson B.V., M.J Ghafri., Al-harthy A.S.M. - The Use of Carbon Steel in Highly Sour Oil and Gas Production Systems - prepared for presentation of the SPE International Oilfield Scale Conference held in Aberdeen UK, 28 -29 May 2008;

27 Lesto A., Prabhancana Kusumo, D. Supriyatman,- Corrosion Management in Production Pipeline Network Using Risk Management Analysis" prepared for presentation at the SPE Asia Pacific Oil and Gas Conference and Exhibition held in Jakarta, Indonesia, 15–17 April 2003;

28 Macovei N, Tubing and cementing of wells - Publishing House of the University of Ploiesti 1998;

29 Marin, G.- Studies and research regarding the realization of a transportable installation for inserting flexible tubing into wells under extraction, including the eruption prevention system, jubilee session OF "PETROL-GAZE" UNIVERSITY Ploiesti, OIL Equipment section for extraction drilling, Ploiesti 1998

30 Marin, G.- Technologies and equipment for the directed drilling of under-crossing holes, EXPO PETRO GAS SYMPOSIUM - EDITION 3, Bucharest, Sept. 2000

31 Mingjie K, J. Bales, Corrosion Behavior of Various 13 Chromium Tubulars in Acid Stimulations Fluids, presented at 1st International Symposium on Oilfield Corrosion held in Aberdeen 2004;

32 Miron C., Methods, technologies and products for restoring and increasing the natural permeability of the strata in order to increase the influx of oil and gas and the receptivity of injection wells Technical Publishing House, Bucharest, 1999;

33 Montgomery C., Fracturing Fluid Components. In Effective and Sustainable Hydraulic Fracturing 2013 May 17. IntechOpen, https://www.intechopen.com/books/effective-and-sustainable-hydraulic-fracturing/fracturing-fluid-components

34 Prantil, V. C., Callabresi, M. L., Lathrop, J. F., Ramaswamy, G. S., Lusk, M. T., 2003. Simulating Distortion and Residual Stresses in Carburized Thin Strips, ASME, J. Eng. Mater. Technol. 125(2), doi:10.1115/1.1543973, pp. 116-124.

35 Restarick, H.L., Mechanical Fluid-Loss Control Systems Used During Sand Control Operations, SPE 23741 paper presented at SPE International Symposium on Formation Damage Control, Lafayette, LA, February 26-27, 1992;

36 Serban V., A. Raduta, "Politehnica" University of Timisoara, Materials Science and Engineering, Edition III, Politehnica Publishing House 2014;

37 Serban V., "Politehnica" University of Timisoara, Course 13, 2009, http://www.mpt.upt.ro/doc/Curs%20finale%20IE-%202012.ppt

38 Serban V., "Politehnica" University of Timisoara, Materials Science, Course "Thermal treatments applied to Fe-C alloys", https://drive.google.com/file/d/0BxVb8sILHHT1YUlxd1RWNDZtbmM/view

39 Silvana Rossy Brito, Ivan Bastos, Hector Reynaldo Meneses Costa, José Brant de Campos, "Correlation Between Chemical Composition and Adherence of Cr and Co Coatings Deposited by Electric Arc", Journal of Adhesion · May 2014;

40 Suciu V., M.V. Suciu, Studiul Materialselor, Ed. Fair Partners, 2008, 255 pages, ISBN 978-973-1877-01-3, http://marcel.suciu.eu/Cartea_Std_Mater.pdf

41 Sunshil, S., 2012. Review of heat transfer augmentation for cooling of turbine blade type by geometrical modification to the surfaces of blades, International Journal of Research in Engineering and Technology, ISSN 2319-1163.

42 T. auf dem Brinke, Plasma-Assisted Nitriding Offers Production Flexibility, Industrial Heating, May 2001, https://www.industrialheating.com/articles/84271-plasma-assisted-nitriding-offers-production-flexibility

43 Tremoulet O, Raghavan C, Madden K. Plunger seal assembly for a high pressure pump. WIPO Patent No. 1999014501; 1999.

44 Tudor I., G.V Rapeanu, Corrosion Engineering, vol 1-2, Publishing House of the University of Ploiesti 2002;

45 Utu Dragos, "Habilitation thesis - Coating and remelting techniques with layers resistant to corrosion and wear" Universitate Politehnica Timisoare 2019; http://docplayer.ro/178445172-Tez%C4%83-de-abilitare-conf-dr-ing-ion-drago%C8%99-u%C8%9Bu-universitatea-politehnica-timi%C8%99oara- faculty-of-mechanic%C4%83.html ;

46 Uțu I.D., I. Mitelea, Introduction to Surface Engineering, Politehnica Timişoara Publishing House, 2018;

47 Vetter J., J. Crummenauer, T. auf dem Brinke, Corrosion Protection by Plasma Heat Treatment IONIT OX®, AMS/TMS Fall Meeting Conference, Columbus, Ohio, Oct. 2002, https://www.researchgate.net/publication/260016884_Corrosion_Protection_by_Plasma_Heat_Treatment_IONIT_OXR

48 Vetter J., Thermochemical Heat Treatment with Added Corrosion Protection and Wear Protection ICMCTF Conference, April 2003, San Diego, https://www.researchgate.net/publication/260035060_Thermochemical_Heat_Treatment_with_Added_Corrosion_Protection_and_Wear_Protection_-_invited_talk_ICMCTF_2003_San_Diego

49 Wang C. A. Neville, Understanding Inhibitor Action on Components of Erosion, Corrosion and their Interactions in CO2 -containing Slurries, presented at 1st International Symposium on Oilfield Corrosion held in Aberdeen 2004;

50 Yang J, Yu Z, Fei X, et al. Technical progress of hydraulic reciprocating seals.

51 Yi Zhou, Zhiqiang Huang, Yan Bu, Chengsong Qiu, Yuan Yuan, - Simulation studies on drilling mud pump plunger seal failure under ultrahigh pressure and ultradeep conditions, Elsevier, 2014.

52 Zhanghua Lian a, Yang Liu a, Tiejun Lin a, Li Li b, Zhongqing Lei c, Chuanjun Han - Study on the fluid flow rule of five-cylinder plunger pump hydraulic, End Petroleum 4 (2018).

53 Zhu Weibing, Yan Jingjiang, Heshun Wang - Structure Analysis and Design Improvement of Plunger Seal Pair in Fracturing Pump, American Journal of Engineering and Technology Management, Volume 1, Issue 3, October 2016.

54 *** Handbook of Thermal Spray Technology, ASM International, Edited by J.R. Davis

55 *** http://kermetico.com/hvaf-vs-hvof-coating

56 *** http://www.comoti.ro/ro/Proiect_METAXLE.htm?pag=3

57 *** http://www.confind.ro/hvof.html

58 ***www.hunprenco.com/process/details/hvof_high_velocity

59 *** https://kermetico.com/applications/pump-plunger-coating-equipment

60 *** https://plasmajet.ro/metalizarea-cu-plasma/

61 *** 1991. ASM Handbook, Vol. 4: Heat Treating, ASM International, ASM International Library of Congress.

62 *** 2014. Matlab-Simulink (MATLAB®) (http://www.mathworks.com/control-systems)

63 *** Technical book ACF 700, ACF 800 - IPCUP Ploiesti Archive;

64 *** Earthworks, Hydraulic fracturing, Issue 101, Dec. 2017, https://www.earthworks.org/issues/hydraulic_fracturing_101/#FOOTNOTE1