ГОДИШНИК НА МИННО-ГЕОЛОЖКИЯ УНИВЕРСИТЕТ "СВ. ИВАН РИЛСКИ", Том 49, Св. I, Геология и геофизика, 2006
ANNUAL OF THE UNIVERSITY OF MINING AND GEOLOGY "ST. IVAN RILSKI", Vol. 49, Part I, Geology and Geophysics, 2006

# EXPERIMENTAL RESEARCHES REGARDING THE DRILLING PIPE LOADINGS IN THE STARTING PHASE OF THE MINE DRILLING PROCESS

***Simion Parepa***

*Petroleum-Gas University of Ploiesti, Ploiesti 2000, Romania*

**ABSTRACT.** The drill column used for mine shaft drilling (exploitation and aerating) consist of elements (bit, drill stabilizer, drill collars and drill pipes) having large diameters, masses and mass moments of inertia respectively. As a result, the dynamic moments and dynamic loadings are important, especially during the transient periods of the rotating motion. For that reason it is necessary the knowledge of the pipe dynamic loadings in the starting phase of the drill column rotating motion. As follow, in the paper the experimental research results are presented by using the stress-resistive method concerning the dynamic loadings (physical actions and stresses) of the drilling pipe body of 10¾ inches and of its zones with stress concentrators. There are also specified the experimental conditions during the drilling of a mine shaft having a diameter of 142.5 inches (3.62 m) by using a drilling rig of F320-3DH-M type, with surface driving; there are also presented some aspects of the experimental research method; there are exposed the time variation laws of the dynamic actions (of the torsion moment, bending moment and of the axial force/traction force), and of the corresponding stresses, and of the equivalent stress in the mentioned zones of the drilling pipe, in two cases of starting; it is shown the processing method of the dynamic recordings and the results are interpreted. The loadings variability during the rotating motion starting of the drill string proves the existence of a quick propagation process of the cracks initiated in the zones with stress concentrators of the drilling pipes.

**ЕКСПЕРИМЕНТАЛНИ ИЗСЛЕДВАНИЯ ОТНОСНО НАТОВАРВАНИЯ НА СОНДАЖНАТА ТРЪБА В НАЧАЛНАТА ФАЗА НА СОНДАЖНИЯ ПРОЦЕС**

***Симион Парепа***

*Университет по петрол и газ, Плоещ, Плоещ 2000, Румъния*

**РЕЗЮМЕ.** Използваната колонкова пробивна сондажна апаратура е съставена от различни сондажни елементи с много голям диаметър. Това прави динамичните моменти и натоварвания важни, особено по време на задвижване на въртящия се механизъм. По тази причина са необходими познания относно натоварванията на сондажната тръба в момента на задвижване на пробивния свредел. Последователно в доклада са изложени резултатите от експериментални изследвания, чрез използване на метода на съпротивителното налягане, относно активните натоварвания (физически въздействия, напрежения) на тялото на сондажна тръба от 10¾ инча и в зоните с концентрация на налягането. Маркирани и анализирани са различни експериментални резултати, получени при използването на вариантни размери и видове сондажни устройства.

## Introduction

The rotary-hydraulic drilling process of the mine shafts by using surface rigs is characterized by a dynamic regime (Parepa and Ilias, 2005), determined by the phases: the drill string starting with its idle rotation; the bit landing on the bottom of the shaft with a certain weight; the running in regime during the proper drilling; the bit rise from the bottom and the idle rotation in order to correct the part of the drilled hole by realizing the drilling mud intense circulation in order to eliminate the rock cuttings which load the rollers of the bit. These phases include the appearing of some complex loadings (axial force, torsion moment and bending moment) with variable intensities and having variable time cycles and acting on the drilling pipes. Under the influence of the repeated loadings, transformations with the evolutive disturbances may be produced in the drilling pipe material, which will characterize the fatigue phenomenon. Due to the large inertia moments of the mining drill string elements, the dynamic loadings of the drill pipes are important, especially in the transient periods of the rotating motion, and can accelerate the disturbance process in the areas with stress concentrators (having a technological or constructive nature) by increasing the crack propagation speed until their critical size.

The object of the experimental researches presented in this paper is about the drilling pipes having a nominal diameter of 10¾ " (Fig. 1), used for mining shaft drilling with a diameter of 3.62 m by using a drilling rig of F320-3DH-M type. The rotary system of the mentioned rig is made up of two groups of electro-hydrostatic driving, with hydrostatic units having axial plungers, of rotary table, kelly and drill string (see Parepa and Ilias, 2005).

In the frame of this work we are concerning with the first phase of the drilling process, that is the starting phase of the drill string rotating motion.

## Experimental recording realization

The experimental researches were developed in the frame of an extensive research program of the mine drilling process (Parepa, 2001; Parepa and Ilias, 2005) and of the dynamic loadings of the drill string of 10¾" (Parepa, 2006). They imposed the construction of three loading captors (Parepa, 2006) called CS1, CS2 and CS3, being represented by three drill pipes, one of them having air tubes (CS1, Fig. 1) and the other two without air tubes (CS2 and CS3), equipped with strain gauges protected by special sleeves (Fig. 2).

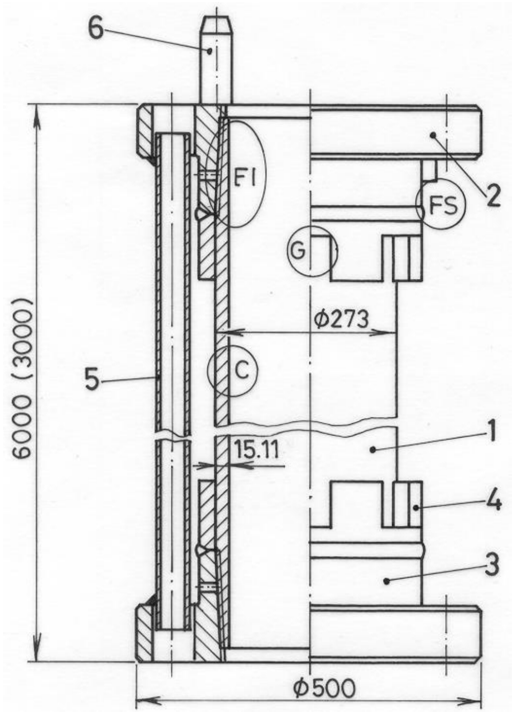


**Fig. 1. Drilling pipe with air tubes: 1 – body; 2 – upper flange; 3 – lower flange; 4 – crenellated support collar; 5 – air tube; 6 – centering and torsion moment transmission bolt**

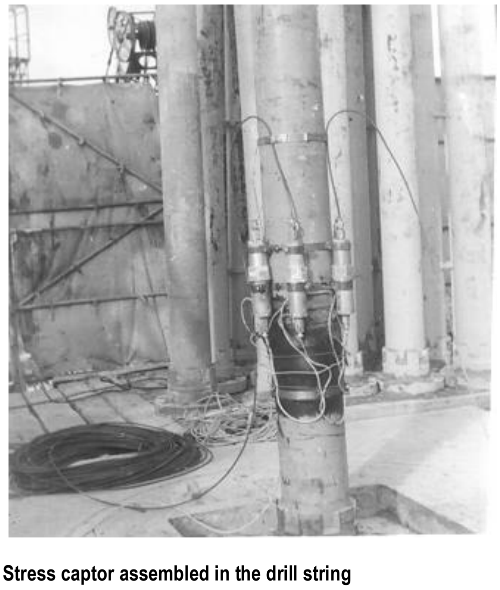

**Fig. 2. Stress captor assembled in the drill string**

By means of these captors, the drill pipe loadings in three zones were recorded (Fig. 1): C – the body zone; FS – the flange shank zone in the close proximity of the welding seam between it and the collar; G – the drilling pipe body zone in the cup up part of the support collar, in the close proximity of the welding seam between the collar and the drill pipe. In zone C each of the captors has the possibility to measure separately the strain due to the axial force (F), the torsion moment ($M_T$), the bending moment ($M_{Bend}$) and the total/complex strain of the drill pipe body.

The strain-measuring chain was made up of loading captors, the binding cables, having large lengths corresponding to the captor emplacement depths inside the drill string, the collector with sliding contacts placed in the upper part of the drill string, and the dynamic recording electronic system (Parepa and Ilias, 2005).

The dynamic measurements were carried out during the drilling of a mine shaft having a diameter of 3.62 m by using 48 drilling pipes (among them 6 drilling pipes were with air tubes, and the others without air tubes), and a depth assembly made up of a bit with multiple rollers of SRM 3600x10¾ type, a roller stabilizer of SR 3600x10¾ type, and a "drill collar" made up of annular sleeves of cast steel ("doughnut weights") having a diameter of 1.4 m.

Recordings during the drill string starting in two cases were carried out: with a single generator group running in stationary regime and the subsequent starting of the second group, and with the two generator groups being in stationary regime of running. It is stated that a generator group is made from an asynchronous electric motor having its rotor in short-circuit, and a hydrostatic generator with axial plungers.

## Experimental results and their analysis

Further, the recordings concerning the loadings of the drilling pipe with air tubes (CS1) assembled on the upper part of the drill string during the starting are presented and analysed.

The external surface of the drill pipe was considered as a plane surface characterized by normal stresses ($\sigma_x$ and $\sigma_y$), tangential stresses ($\tau_{xy}$ and $\tau_{yx}$), and by linear strains ($\varepsilon_x$ and $\varepsilon_y$) and angular strains ($\gamma_{xy}$), depending not only on the measuring point, but on the considered directions. The mathematical expressions used for determination of the main specific deformations ($\varepsilon_{1,2}$), the main normal stresses ($\sigma_{1,2}$), the main tangential stresses ($\tau_{1,2}$) and the angle ($\varphi_1$) made up by the main direction with direction x, of the drill pipe axis, as well as the relationships used for calculations of the tensile stress ($\sigma_F$), of the bending stress ($\sigma_{Bend}$), of the maximal tangential stress ($\tau_T$), and also the calculation formulas of the tensile force (F), of the bending moment ($M_{Bend}$), and of the torsion moment ($M_T$) are those known from the speciality literature. For calculation of the equivalent stress ($\sigma_{Eqv}$) in one point of the external surface of the drill pipe body, the theory of the deviation potential energy it was admitted. Calculation programs were made up by using the MATLAB language for processing the recordings.

The analysis of the captor CS1 dynamic responses is further made, separately for the zones C, G and FS.

**Zone C**

In Fig. 3 the time variation laws of the physical actions (F, $M_{Bend}$ and $M_T$), and in Fig. 4 the stress ($\sigma_F$, $\sigma_{Bend}$ and $\sigma_{Eqv}$) variation laws depending on the same physical size, in case of starting by using both of the generator groups being in stationary regime, in accordance with the recording No. 26 are presented.

It is ascertained that the torsion moment may reach the maximal measure ($M_{T.M}$), of 75.2 kNm, at the time of 1.52 s, recording great increases ($\Delta M_T$), of {13.3; 12.3; 10.8; 8; 6.9; 4.4}·kNm, in short time ranges ($\Delta t$) of 0.8 s, until the maximal measure. At the time 7.76 s the minimal measure of 2.57 kNm is reached, and at the time of 10.64 s it is considered that the torsion moment is established at the measure ($M_{T.st}$) 6.93÷7.19 kNm (see Fig. 3). It will result that the maximal dynamic torsion moment ($M_{T.d.M}$) has a measure of 68.14 kNm, and the maximal dynamicity coefficient, determined by the expression

$$k_{d.M} = \frac{M_{T.M}}{M_{T.st}} = 1 + \frac{M_{T.d.M}}{M_{T.st}} \, , \qquad (1)$$

has the value 10.65.

The axial force (F) remains practically constant, F=1311 kN, in the range [0; 3.6]·s, it records little oscillations between 1302 kN and 1311 kN, in the range [3.6; 5.6]·s where oscillations of the torsion moment may be observed, then it returns to measures of about 1311 kN in the following range, until the time of 7.12 s. In the period [7.12; 8.96]·s, when the torsion moment has minimal measures, the axial force has two disturbances, recording the maximal measure of 1337 kN (see Fig. 3).

The bending moment ($M_{Bend}$) has oscillations with measures ranging between -3.47 kNm and +0.32 kNm, in the well-marked variation range of the torsion moment, and higher oscillations between -4.95 kNm and +3.07 kNm, in the range where the torsion moment decreases towards the minimal measure, and then increases to the stabilization measure (see Fig. 3).

According to the Fig. 4, the time variation laws of the tensile stress ($\sigma_F$) and the bending stress ($\sigma_{Bend}$) have identical shapes to those of the actions determining them. The tensile stress has the average measure of 107.3 MPa, the quadratic average deviation ($d\sigma_F$) of 0.548 MPa, the maximal measure of 109.2 MPa and the minimal measure of 106.3 MPa.

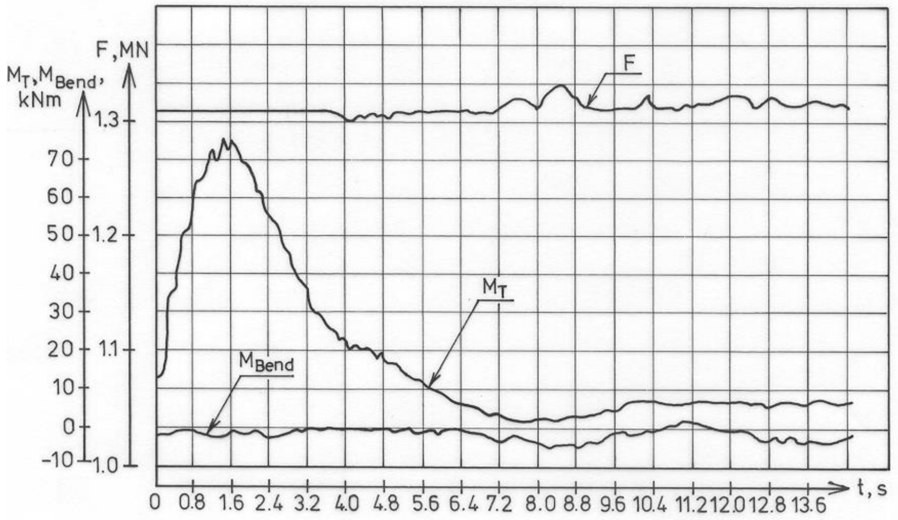


**Fig. 3. Time variation of the axial/tensile force (F), torsion moment ($M_T$) and bending moment ($M_{Bend}$) which loads the cross section of the drilling pipe body CS1, during the drill string starting by using both of the generator groups**

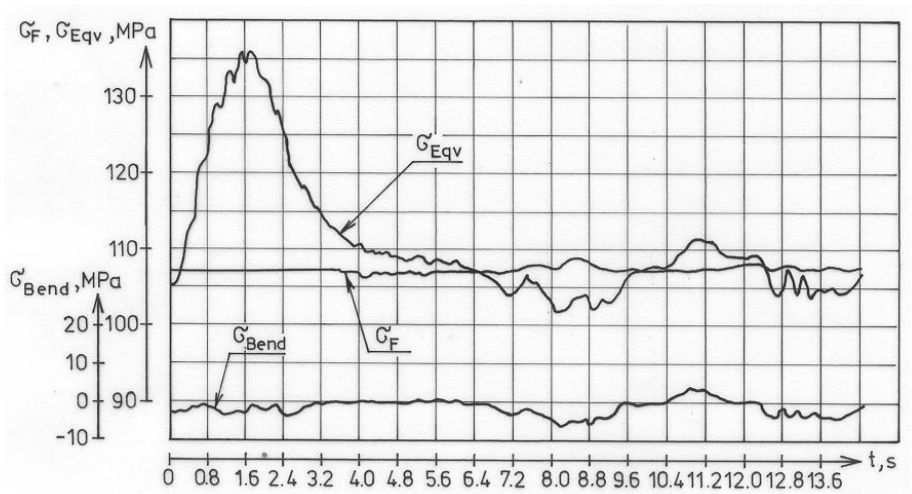


**Fig. 4. Time variation of the axial stress ($\sigma_F$), bending stress ($\sigma_{Bend}$) and equivalent stress ($\sigma_{Eqv}$) in the cross section of the drill pipe body CS1, during the drill string starting by using both of the generator groups**

The bending stress is characterized by the average measure of -1.44 MPa, the quadratic average deviation ($d\sigma_{Bend}$) of 1.90 MPa, the maximal measure of 2.84 MPa, and the minimal measure -6.31 MPa. The torsion stress ($\tau_T$) has the maximal measure of 50.3 MPa and the minimal measure of 1.72 MPa. Regarding the equivalent stress ($\sigma_{Eqv}$) this records the maximal measure of 136.3 MPa at the time of 1.76 s and the minimal measure of 102.4 MPa at the time of 8.16 s from the starting moment. The direction of the main stress ($\sigma_1$) will form with the axial direction of the drill pipe the angle $\varphi_1$ having the average value of 0.133 degrees, the maximal value of 0.383 degrees, and the minimal value of 0.016 degrees.

Other measures of the physical sizes characterizing the loading variations in the cross section of the drilling pipe body CS1 during the drill string starting with both of the generator groups being in stationary regime of running in Table 1 are presented. In this table, were marked with f the physical size, $f \in \{F, M_T, M_{Bend}, \sigma_F, \tau_T, \sigma_{Bend}, \sigma_1, \sigma_2, \tau_1, \varphi_1, \sigma_{ech}\}$, with $f_a$ – the average measure of f, with $f_M$ – the maximal measure, with $f_m$ – the minimal measure, and with df – the quadratic average deviation of the phisical size (f) measures.

From kinematical point of view, the starting phase is presented by the time variation law of the angular speed ($\omega_K$) of the kelly (see Fig. 5). The angular speed suddenly increases to a maximal measure of 1.563 rad/s, after that decreases to a minimal measure of 0.463 rad/s, at the time of 1.6 s, and increases again, but a little slower, until it is established at a measure of 1.19 rad/s.

In accordance with the recording No. 32, in Fig. 6 the time variation of the equivalent stress in zone C, in the case of drill string starting by means of only one generator group running in stationary regime and the subsequent starting of the second generator group, is presented. It may be noticed that this variation is less marked than that corresponding to the starting with both of the generator groups, which initially are found in stationary running regime (see Fig. 4). In this way, the maximal measure of 120.9 MPa it is reached at a time of 3.4 s that is after a time range of 1.93 times higher than in the previously case. At the time of 10.8 s, after to be set running the second generator group, it is reached the second peak with a measure of 107.6 MPa. The torsion moment has a maximal measure of 48.5 kNm that is with 35.5% lower than the maximal measure of the torsion moment which appears in the first case.

Tabel 1

*Measures of the phisical sizes characterizing the loading variation in the cross section of the drilling pipe body CS1 during the drill string starting by using both of the generator groups.*

| f | F, kN | $M_T$, kNm | $M_{Bend}$, kNm | $\sigma_F$, MPa | $\tau_T$, MPa | $\sigma_{Bend}$, MPa | $\sigma_1$, MPa | $\sigma_2$, MPa | $\tau_1$, MPa | $\varphi_1$, degrees | $\sigma_{Eqv}$, MPa |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $f_a$ | 1314,1 | 23,43 | -1,08 | 107,3 | 15,66 | -1,44 | 109,9 | -4,03 | 56,98 | 0,133 | 112,1 |
| $f_M$ | 1337,3 | 75,20 | 3,07 | 109,2 | 50,26 | 2,84 | 125,4 | -0,03 | 72,52 | 0,383 | 136,3 |
| $f_m$ | 1301,9 | 2,57 | -4,95 | 106,3 | 1,72 | -6,31 | 102,3 | -20,24 | 51,17 | 0,016 | 102,4 |
| df | 6,73 | 22,75 | 1,42 | 0,55 | 15,20 | 1,90 | 5,88 | 5,98 | 5,87 | 0,120 | 9,07 |

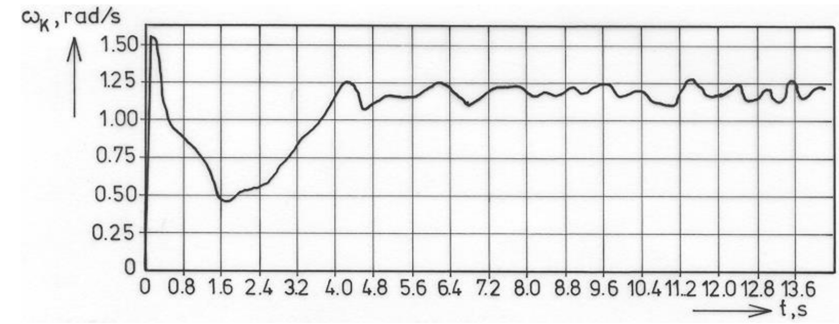


**Fig. 5. Angular speed variation of the kelly ($\omega_K$) during the drill string starting by using the two generator groups**

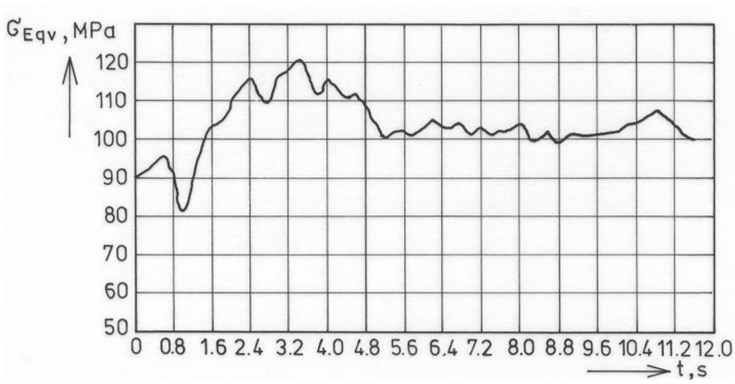


**Fig. 6. Time variation of the equivalent stress ($\sigma_{Eqv}$) in zone C of the drilling pipe body CS1 in the case of starting of the drill string with a single generator group running in stationary regime and the subsequent starting of the second group**

**Zone G**

In accordance with the recording No. 34, in Fig. 7 the equivalent stress variation in zone G, in case of the starting with a single generator group, initially being in stationary running regime and the subsequent starting of the second generator group, is presented.

A very well-marked variation of the equivalent stress in the recording period of 15.68 s may be observed. The initial measure of the equivalent stress is 84.7 MPa. For a duration of [0; 1.52]·s some oscillations of the equivalent stress with increases of {3; 2; 2; 6; 8; 6}·MPa in short time ranges of {0.08; 0.08; 0.08. 016; 0.16}·s may be ascertained. After that, other increases of {4.5; 7.0; 7.5}·MPa in time ranges of 0.16 s will follow. In the period [1.84; 3.04]·s some oscillations having rising amplitudes from 1.5 MPa to 2.5 MPa appear again. At a time of 3.04 s the maximal measure of 132.8 MPa is reached, a measure which is larger with about 12 MPa than the maximal measure of the equivalent stress recorded in the same conditions in the cross section of the drilling pipe body (zone C). After that the maximal measure has been reached the equivalent stress will decrease in the range [3.04; 7.68]·s, the minimal measure being 70 MPa at the time of 7.68 s. At the time of 9.6 s, after having been set running the second generator group, the second peak is reached, which is larger about with 20 MPa than the corresponding measure of the equivalent stress recorded in the same conditions in the cross section of the CS1 drilling pipe body. After that it follows another equivalent stress decrease with stronger oscillations.

**Zone FS**

The analysis of the stresses in zone FS of the drilling pipe CS1 is carried out only in the case when the drill string starting is made up with a single generator group. So, in Fig. 8 the time variation of the equivalent stress in this zone by processing the recording No. 36 was presented. From the analysis of this diagram the following observations may be drawn out: the equivalent stress variation at starting is less marked, the initial measure being 90.7 MPa, the minimal measure 90.5 MPa, and the maximal measure 112.9 MPa; the maximal measure is reached at the time of 5.6 s; the maximal measure of the equivalent stress is with 8 MPa smaller than the maximal measure of this stress determined in the same conditions in the cross section of the drilling pipe body CS1, and with 20 MPa smaller than the maximal measure of the equivalent stress in zone G in starting state (see the subchapter Zone G); after the equivalent stress decreases at the measure of 91.2 MPa in the range [5.60; 9.84]·s, the second increase is recorded, corresponding to setting in running of the second generator group, until the measure of 111.3 MPa, in the time range [9.84; 17.44]·s; two periods, having the duration of 9.4 s, of variation of the equivalent stress about of 20 MPa between the approximate measures of 91 MPa and 111 MPa may be ascertained.

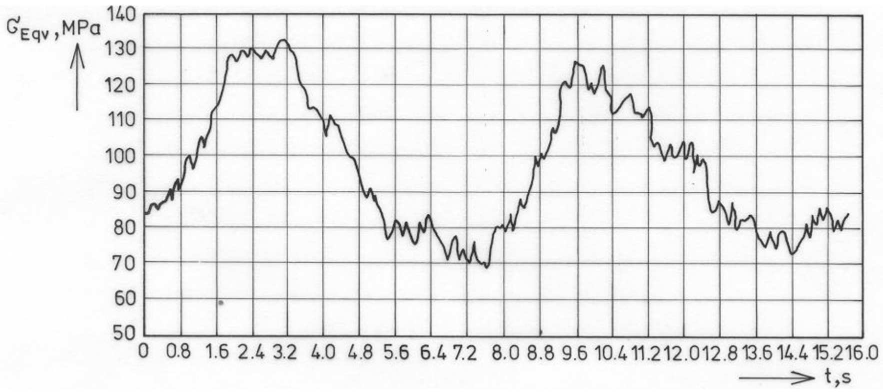


**Fig. 7. Variation of the equivalent stress ($\sigma_{Eqv}$) in zone G of the drilling pipe CS1 in the case of starting with a single generator group being initially in stationary regime of running and the subsequent starting of the second group**

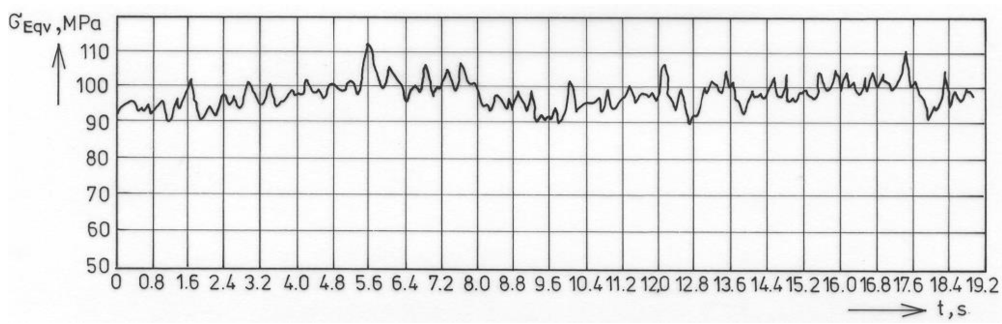


**Fig. 8. Time variation of the equivalent stress($\sigma_{Eqv}$) in zone FS of the drilling pipe CS1 in the case of starting of the drill string with a single generator group running in stationary regime and the subsequent starting of the second group**

## Conclusions

The drilling process of the mining shafts is characterized by more phases, among them being the starting phase of the drill string rotating motion which has an important part regarding the pipe dynamic loadings. The real complex loading of the drilling pipes of 10¾" (in the body zone – zone C – and in zones with stress concentrators – zones G and FS), during the drill string starting was determined in an experimental way, by using the stress-resistive method. The experimental research method of the dynamic loadings (of the actions and dynamic stresses) of the drilling pipes of 10¾", as a concrete realization method, represented a new achievement. Its application implied the construction of some loading captors and of some devices, among them being mentioned the collector with sliding contacts, which allowed the electric signal transmission from the measure points finding on the drilling pipe in rotating motion to the electronic apparatus necessary for their processing and recording.

The dynamic loading analysis of the drilling pipe body CS1 (zone C), at the drill string starting in the two cases (with both of the generator groups being in stabilized regime of running – idle running – and with a single generator group in idle running regime and the subsequent starting of the second group) emphasizes a series of conclusions which are further exposed. So, in the case of starting by using a single generator group and the subsequent starting of the second group, the drill string loading is smaller, the maximal measure of the torsion moment being with 35.5% smaller than the maximal measure of the torsion moment which appears in the case of starting with both of the generator groups. Further, from point of view of the dynamic loadings, the drill string starting must be carried out with a single generator group, and the subsequent starting of the second group. The maximal torsion moment, which loads the drilling pipe CS1 in case of starting of the drill string with both of the generator groups, has the measure of 75.2 kNm, from which 90.6% represents the measure of the dynamic moment corresponding to a maximal dynamicity coefficient having a high value and namely 10.65. In accordance with the design conditions, the maximal measure of the torsion moment, which loads the drilling pipes of 10¾", is limited to 78.5 kNm, when the maximal axial running load is of 150 tf (1471.5 kN). If we take into account the fact that the axial force recorded in the moment when it was reaching the maximal measure of the torsion moment was only of 1311 kN, it will result that it is possible the exceeding of the torsion moment maximal measure imposed by the designer when the load from the hook reaches the maximal measure of running. Taking into account the maximal measure of the equivalent stress resulted in the time when the starting by means of two generator groups is recorded, for the tensile yield stress of the material of which the drilling pipe body is made up a safety coefficient of 3.74 is obtained.

The analysis of the stress state of the drilling pipe CS1 in zone G, carried out only in the case of the drill string starting by means of a single generator group and the subsequent starting of the second one, it may be shown that this zone with stress concentrators, represented by passing from the flange collar to the drill pipe body and joining with lateral and frontal welding of the two elements, is characterized by equivalent stresses with higher measures, at least with 10% than those appearing in the cross section of the drilling pipe body (zone C) and by far well-marked oscillations. The direct gauging of the loading captors displayed (according to Parepa, 2006) the existence of some pre-tension state in zone G. This pre-tension state influences the stresses due to the actions during the drilling, and has an important role in yielding of the fatigue phenomenon. So, it is demonstrated that zone G makes up a dangerous zone of the drilling pipe from point of view of the equivalent stress and of its variability, a zone which is favorable to the appearance of fatigue disturbances, especially because this represents, with a great likelihood, the place of crack nucleation. Also, the dynamic equivalent stress variation during the starting hastens the disturbance process in this zone, by making greater the crack propagation speed, as it was ascertained during the measurements. In this way, after about 16 hours, how much the measurements – realized in different conditions (of drilling with different regimes, of starting of the drill string, and of its idle running etc.) – lasted, and after the bringing out of the drill string a penetrated macro-crack in the terminal zone of the lateral welding between the support collar and the drilling pipe body, on the base of a crenellation, was observed (see Fig. 9).

**Fig. 9. View of a zone with penetrated macro-crack on the drilling pipe without air tubes, with series 122.**

From the analysis of the stress state in the zone FS of the drilling pipe CS1, may be seen that the butt seam welding between the flange neck and the crenellated collar takes part effectively to taking over of the loads, although it is not realized in this purpose (see Parepa, 2006), but it may be considered that this zone, having stress concentrators, represents a less dangerous one for appearance of fatigue disturbance even than the drilling pipe body, in the conditions when the technology of the welding realization is respected. This thing is due to the larger section of the flange neck and due to better technological conditions for the welding realization.

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Recommended for publication by Department of Drilling and Oil and Gas Production, Faculty of Geology and Prospecting