Influence of Operating Conditions of the Steel Cord on the Structure and Selected Mechanical and Technological Properties of High Carbon Steel

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Abstract— *When buying tires, we would like them to serve us as long as possible. Experts of the independent organisation Dekra, based on case studies found that after six years the risk of tire failure increases drastically, which is why they recommend replacement of tires after six years of operation at the latest. The results of the presented studies have shown that operation of the car tires in such extreme conditions as continuous contact with ground, frequent braking and repeated hitting against bumps in the road leads to delamination of the steel material of belting and decrease in its mechanical properties by about 35-48% compared to the reference material.*

Keywords—- Eutectoid Steel, Cord, Belt, Non-Metallic Inclusions

I. INTRODUCTION

Car tire is the outer part of the wheel of open section, applied to the wheel rim and filled with pressurised air. It is a part of the vehicle contacting with the ground, can carry the weight of the vehicle, the driving, braking and turning forces, as well as provide the basic shock absorption during the ride [14,15]. Build of the car tire is complex and its main parts are: tread, belt, matrix, filler and bead wire. The tread is responsible for tractive adhesion and driving a car. The foot consists of a bead wire and a filler and it enables assembling a tire at the wheel rim and provides for tightness of that junction. The matrix is the primary load-bearing part in the whole structure, providing for dimensional stability and resistance to tearing. The other, extremely important part is the belt, the basic function of which is stiffening of the tire front and providing resistance to devastating effects of the centrifugal force at high speeds. The belt consists of one or several layers of steel cord, the layer of resistant wires of 0,2-0,5 mm diameter, made of pearlite steel [10, 5, 11].

The eutectoid steels containing from about 0,8 to 0,95% of C belong to the group of unalloyed steels of the quality class designated for cold drawing or rolling [1,2]. They have found application mainly as the wires for production of steel cord used for reinforcing tires (PN-EN 10323:2005 (U)), hoses (PN-EN 10324:2006) or production of ropes (PN-EN 10264-1:2005) [4,8]. Their chemical composition and mechanical properties should comply with the PN-EN 10323:2005 (U) standard [10,4]. However, it should be remembered that mechanical properties, and mainly the tensile strength, are highly dependent on the percentage content of steel components, especially on contents of chromium, silicon and manganese. In the annealed state the eutectoid steels have the highest strength in relations to the remaining unalloyed steels [4]. At the same time the steels are characterised with particularly low share of non-metallic inclusions and limited contents of chromium and nickel, which affect the prolongation of pearlite transformation time [4,8].

World producers of pearlite steel wire do not intend to reveal the secrets of the plant and do not give many details of the technological process [10,5,11]. However, it is known that in the process of cold drawing of wire the deformation strengthening of material takes place and decreasing of its plastic properties which may lead to destruction of the material caused by its decohesion [2,4]. In order to continue the cold plastic working between subsequent shaping operations a patenting has to be carried out for plasticising the material. Patenting consists in heating up the wire to temperature of austenitising, i.e. to the A_{c3} temperature range (850-1100°C) followed by cooling for some time, most frequently in lead or in salty bathes, to temperatures below A_1 (727°C), enabling obtaining the structure of fine-lamellar pearlite of high ductility [4,8,16].

As standard, the wire rods of 6.5 to 5.5mm diameter and carbon content of 0.65-0.80% are used for production of steel cord C [5,11,7,9]. However, it has to be remembered that for producing cord of normal quality the wire rods should contain 0.65-0.7% C and have Rm ≥ 1860 MPa, and for production of cord of the special quality 0.68-0.80% C and Rm ≥ 2200 MPa. After the technological process performed in accordance with the schemes described above the patented wires should be characterised with the following mechanical and technological properties:

- the tensile strength R_m = 2450-2750 MPa
- the maximum breaking force F_m = 173-194N
- the test of breaking with the knot F_{mw}, the breaking force at that test should be greater than 60% of the maximum breaking force F_m at the tensile strength test [7,9,17,6].

II. MATERIALS AND METHODS

The object of the studies were two types of wires of the eutectoid steel, the STANDARD specimen of d=0,21 mm diameter, being the not operated finished product coming directly from the manufacturer and applied to the belt in car tires, as well as the EXPLO 1-4 specimens after operation of d=0,26 mm diameter, taken directly from the car tire belts. Purpose of the tests was determining the impact of operating at structure and mechanical and technological properties of eutectoid steel.

For microscopic tests in the etched and non-etched states the light optical microscope NIKON ECLIPSE MA200 with the NIS Elements BR software, as well as the scanning electron microscopes Phenom G2 and JEOL 5800LV were used. The observations were performed at magnifications from 100x to 20.000x.

Hardness measurements were performed with the Vickers method using the MMT-X3 microhardness testing machine according to the PN-EN ISO 6507-2:1999. Time of the measurement was 15s, under the load of 300g.

For the purpose of determining influence of tires operation on basic mechanical properties of the tested wires the static tensile test was performed based at the valid standard PN-EN ISO 6892-1:2010. The tests were performed at the MTS 858 Mini Bionix type testing machine. The percent elongation, due to the small diameter of the tested wire was determined thanks to the measurements at the workshop microscope MWD 2744.

The analysis of the technological properties involved performing the test of unidirectional twisting and the test of contraflexure of the tested wires. The test of unidirectional wire twisting was performed in compliance with the PN-ISO 7800:1996 standard, and the test of bidirectional contraflexure according to the PN-ISO 7801:1996 standard. Both tests were performed with constant speed until the specimen breaking; the tests were conducted in ambient temperature.

III. RESULTS AND DISCUSSION

The microscopic observations of the tested materials in the non-etched state have shown presence of non-metallic inclusions, mainly in the form of oxides. The contaminations were distributed punctually and appeared in quantity from standard 2 to 3 according to PN-64/H-04510 (Fig.1 and 2). It has to be kept in mind that fatigue strength of steel wires is highly depending on metallurgic purity of the material [5,3,18,19]. Presence of non-metallic inclusions, especially in the form of brittle oxides, may cause lowering of the material ductility hindering by that the technological processes, and in specific cases lead even to wire cracking during operation.

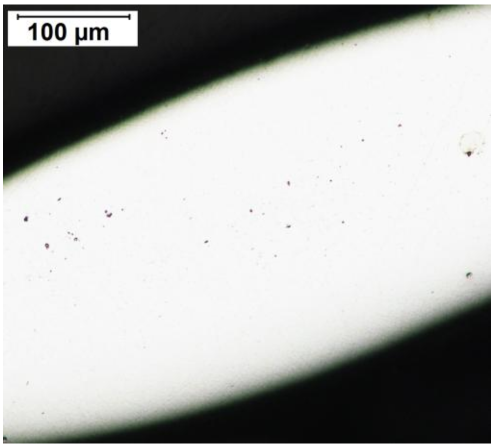

FIG. 1. STRUCTURE OF THE STANDARD SPECIMEN, VISIBLE FINE NON-METALLIC OXIDE INCLUSIONS. NON-ETCHED STATE. LM

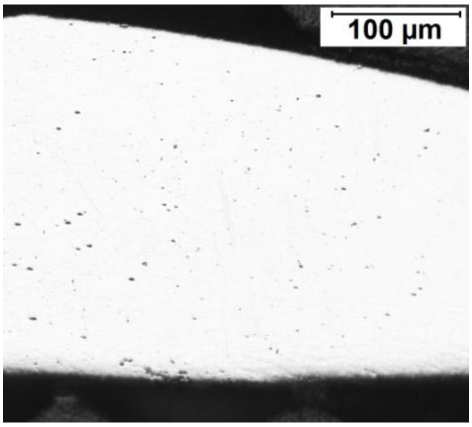

FIG. 2. STRUCTURE OF THE EXPLO 1 SPECIMEN, CLEARLY VISIBLE NON-METALLIC INCLUSIONS IN THE FORM OF PUNCTUALLY DISTRIBUTED OXIDES. NON-ETCHED STATE. LM

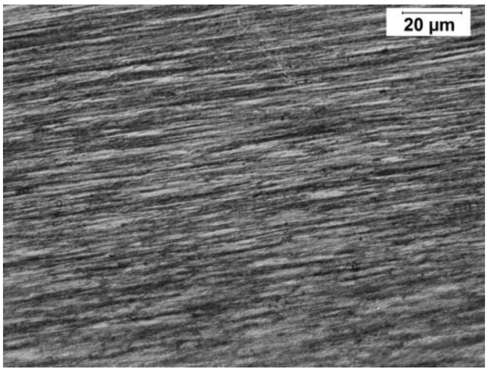

FIG.3. MICROSTRUCTURE OF STANDARD SPECIMEN MATERIAL, VISIBLE STRONG PLASTIC STRAIN OF MATERIAL BEING THE RESULT OF THE APPLIED DRAWING PROCESS. ETCHED STATE. LM

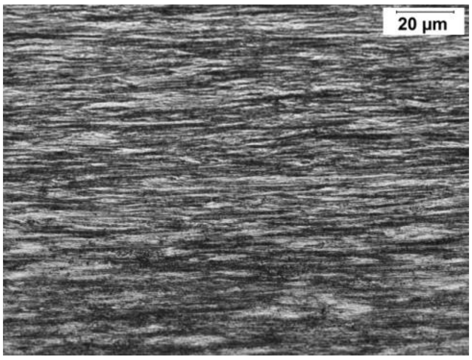

FIG.4. STRUCTURE OF THE MATERIAL AFTER OPERATION IN THE CAR TIRE (EXPLO 2), VISIBLE CLEAR PLASTIC STRAIN AMOUNTING TO ABOUT 80%. ETCHED STATE. LM

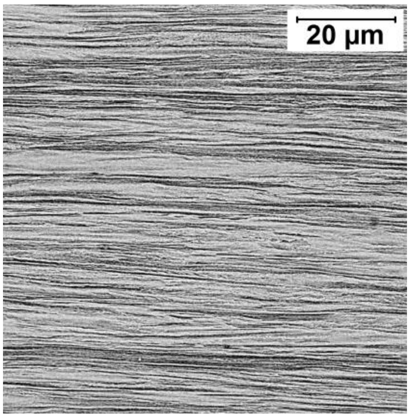

FIG. 5. MAGNIFIED ARE SHOWN IN FIG. 3, VISIBLE THE COHERENT STRUCTURE OF THE STANDARD SPECIMEN. SEM

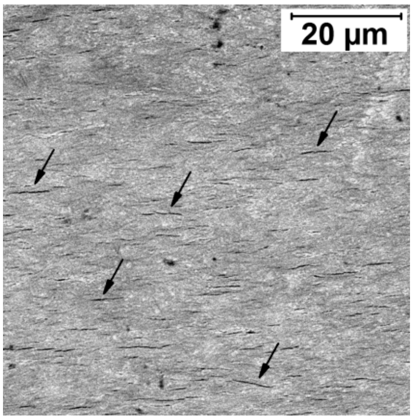

FIG. 6. MAGNIFIED AREA SHOWN IN FIG. 4, CLEAR DELAMINATIONS OF THE MATERIAL POSITIONED IN DIRECTION OF THE APPLIED PLASTIC WORKING. SEM

The microscopic tests performed at sections taken in opposite direction to the plastic working have shown that all the tested wires, according to the recommendations of the PN-EN 10323:2005 (U) standard, were made of unalloyed pearlite steel. As a result of microscopic observations of the specimens made in direction of plastic working it has been found that the tested materials are characterised with high degree of plastic strain of the order of 80-90%, being the result of the cold drawing process applied in technology of steel wires (Fig. 3 and 4).

The initial microscopic tests have not shown the significant differences in structure of the tested specimens, until the further observations with application of the scanning electron microscopy, which revealed the clear influence of operation on structure of the tested material. The results of the microstructure analysis have shown, that during operation of the tire the belt material is destroyed (Fig. 5 and 6). The presence of frequent structure delaminations was observed, oriented in direction of plastic working of the material, the probable cause of the material discontinuities was presence of non-metallic inclusions in the tested materials [5,11,3]. It can be expected, that the observed changes in the structure, will significantly influence the strength and technological properties of the materials, and after exceeding the critical size of the failure may even cause cracking of the wires.

Confirmation of the theory on the negative effect of the observed structure failures on mechanical properties of steel may be found in the results of hardness measurements and strength tests (Table 1). The effect of the car tire operation is a clear reduction in strength properties of the material, the tensile strength for the standard specimen amounted to about 3690 MPa, and for the specimens after operation on average 2292 MPa, hardness for the standard specimen was equal to 766 HV0,3 and after operating it was decreased to the value of about 679 HV0,3. At the same time it has been observed that the material plasticity increased, and the contraction for the standard specimen increased from the value of 14,3% to even 38,5% for the specimen after operation. However, it should be remembered, that increase in necking in the after operation specimen may not necessarily be related to the increase in plasticity of the material, but to the annihilation of the material discontinuities observed in the microscopic tests [5,6].

At the same time the notice is drawn to the clear increase in the Young's modulus, which directly converts into lowering of the wire stiffness and may result in greater tendency of the belt wires to uncontrolled plastic deformations and creation of dangerous tire failures. While analysing the results obtained from the tests the high scatter of the results can additionally be observed, which indicates for different degree of wires wear resulting most probably from their different orientation in the tire belt and by that the various operating load.

TABLE 1
MEASUREMENT RESULTS OF MECHANICAL PROPERTIES OF THE TESTED WIRES SPECIMENS

SAMPLE	Rm [MPa]	E [GPa]	Z [%]	HV 0,3
STANDARD	3690	51	14,3	766
EXPLO 1	2260	157	23,1	683
EXPLO 2	2430	134	38,5	699
EXPLO 3	2147	120	19,2	654
EXPLO 4	2279	139	34,6	669

As a result of the performed technological tests of the unidirectional twisting and contraflexure of the tested wires it has been found that the increase in necking in the after operation specimens observed in the previous tests is definitely not related to increase in the material plasticity. The plasticity of the material clearly decreases, the number of turns in the torsion test drops from 185 to about 100, and the number of contraflexures in the test from 114 to about 45 (Table 2). It follows unambiguously that the long-time operation of car tires leading to creation of structure delaminations of the steel belt material results in decrease in its mechanical, plastic and technological properties.

TABLE 2
RESULTS OF THE TECHNOLOGICAL TESTS OF THE WIRES

SAMPLE	NUMBER OF TURNS IN THE TORSION TEST	NUMBER OF CONTRAFLEXURES IN THE TEST
STANDARD	185	114
EXPLO 1	92	42
EXPLO 2	112	48
EXPLO 3	94	43
EXPLO 4	89	46

IV. CONCLUSION

The results of microstructure analysis of the steel belt wires have shown that during tire operation the material is destroyed. The material structure delaminations observed in the longitudinal sections were visible exclusively in the after operation wires and oriented in the direction of the stress distribution in those components of the tire.

At the same time the analysis of the results of the mechanical property tests have shown that the consequence of the car tire operation is clear decrease in the strength and technological properties of the steel belt wires by some 35-48% in relation to the reference material.

Operation of car tires in such extreme conditions as continuous contact with ground, frequent braking and repeated hitting bumps in the road leads to delaminations of the steel belt material and changes in its mechanical properties [5,12,13]. The necking and the tensile strength directly influence the increase in Young's modulus value, and by that the decrease in stiffness of the steel belt wires which, as a consequence, causes reduction in stiffness of the tire forehead and decrease in the resistance to the devastating effects of centrifugal force at high speeds.

When buying tires, we would like them to serve us as long as possible. Experts of the independent organisation Dekra, based on case studies found that after six years the risk of tire failure increases drastically, which is why they recommend replacement of tires after six years of operation at the latest. The results of the presented studies confirm that each kilometre of the trip distance is not without an impact on the quality of the steel belt and thereby the properties of car tires and most importantly on the driving safety.

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