Influence of tension layer quality on mechanical properties of timing belts

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Abstract. Reinforcement of the tooth belts is the element responsible for the transmission of the torque. Its structure is related to the dynamics of the belt and such important parameters as the stiffness of running stability on pulleys and above all, the pitch stability. The axis of symmetry of the reinforcement in the vertical direction of the belt is the reference point of the belt geometry as well as the neutral axis of stresses caused by bending. On the arc of the contact between belt and pulley, over the reinforcement, the belt is stretched, and below it is compressed. In the tooth belts, there are various solutions of the carrier layer, in terms of the materials used, but also types of fibers, quantity of the fibers, etc. The paper presents the results of analysis of the carrier layer of the most popular tooth belts with T10 and AT10 trapezoidal teeth. The paper shows possible direction of choice of the construction materials of the carrier layer and their importance for the dynamics of the gear with the tooth belt.

Keywords: drive belts, tooth belts, materials in the production of belts

1 The construction of the timing belt

The timing belt as a construction composite is a heterogeneous material. Its main mechanical properties depend on the properties of the reinforcement and the body (Fig. 1).
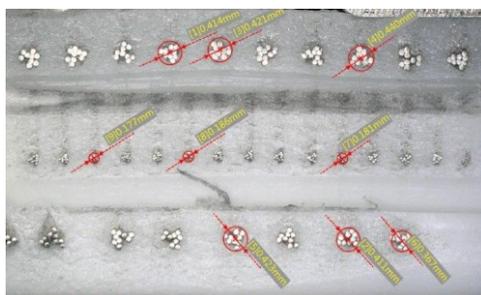

Fig. 1. Cross-section of timing belts with different cord diameter

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The reinforcement otherwise the support layer/fabric or tension cord is responsible for the mechanical strength of the belt and its correct work [1]. The main task of the reinforcement is the transfer of the torque. Its mechanical, physical and thermal properties have a decisive influence on the properties of the whole belt [2]. The proper work of the timing belt, especially in the area of meshing with the pulley, guarantees the correct tooth geometry and pitch stability. The material of the belt is responsible for maintaining the appropriate tooth geometry during belt use. Due to the fact that the article deals with issues related to the carrier layer, the consideration of tooth geometry will be omitted.

The stability of the pitch is called the behavior of the dimension between the geometrical axes of neighboring teeth during operation. In other words, the service life extension of the belt can not be so large that it causes problems with meshing on the belt arches [3]. The belts with imperial dimensions MXL, XL, L, H, XH and T have a higher tolerance for the pitch instability, in contrast to HTD and AT profiles [4]. It is related to the amount of free space which occurs between the teeth of the wheel and the belt during coupling. In a standard drive system in which the belt transmits exclusively the torque from the driving wheel to the driven wheel, the occurrence of the pitch clearance does not affect the quality of the transmission [4]. The situation is different when the belt has other tasks besides transferring the torque. Precise positioning in a certain accuracy requires a proper pitch clearance, because the belt works in two directions. In this case, the pulleys are made in the so-called a zero gap version in Fig. 2. In the case when the belt is subjected to additional processing, e.g. perforation, we obtain additional properties whose workmanship significantly affects both the geometry of the belt and the quality of work. The perforation process itself significantly affects the quality of the holes in the timing belt that performs the conveyor functions, and thus indirectly influences on the strength and durability of the belts [5, 6].
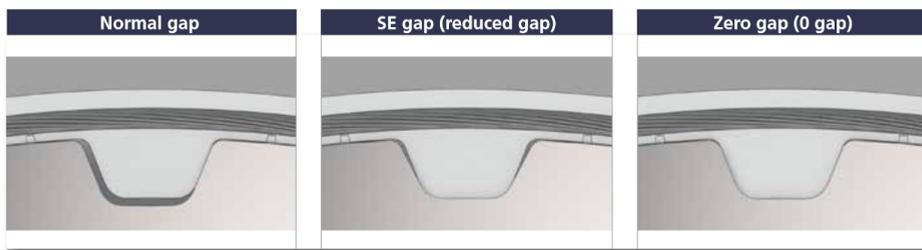
Fig. 2. The types of gaps in pulleys

2 Dynamics properties of the tension layer

The carrying layer during belt operation is subjected to complex loads and mechanical, thermal, chemical and physical phenomena, such as: extensions in the elastic stress area of the active cord, elastic return on the idler, bending on the wheel, twisting of individual wires and fibers , friction between individual wires / fibers, internal intermolecular friction, friction between the carrier layer and the belt material, breaking of single wires causing in result an excessive load on the others, thermal expansion caused by internal and external friction, as well as belt operating temperature, degradation caused by the presence of moisture and an aggressive environment.

The stretching of the active cord and the elastic return on the idler is a phenomenon that occurs in every tensile gear [7]. This phenomenon causes a decrease in torque transfer efficiency and is closely related to elastic slips. Slip is associated with the transmission of torque and occurs at the contact of the belt with the wheel [2]. It involves shortening the belt elongation on the arc of the active belt and the extension of the belt on the passive wheel [7].

The arc of the belt, both active and passive, can be divided into an arc of rest and slip. On the arc of slip there is both a change in belt length, a change in forces in the belt and a change in the linear speed. In the case of an active pulley, negative slip occurs, which causes the shrink of the belt, reduce the circumferential force and the linear velocity in contrast to the situation occurring on the passive wheel. As the load increases, the rest arc decreases. This means that the value of the elastic slip depends on the useful load. There is a limit value of the load for which the rest bow has disappeared, and the arc of slips has covered the entire angle of wrap. In this situation, we are talking about the existence of a permanent slip in the belt gear. The transmission is no longer able to transmit torque. The situation described above applies mainly to gears in which frictional coupling occurs: flat, v-belt, variator, poly v-belt and round [2]. Another situation occures in the case of gears with a timing belt, in which the torque is transferred by friction-shaped coupling [3]. During the operation of the timing belt there is also the phenomenon of elongation of the active tension layer and compensation of elongation in the passive cord. In this case, the wheel slip is minimal, mainly related to the non-linear deformation of the belt material, as well as the displacement of the belt cord relative to the body of belt [7]. These are deformations smaller than those occurring during the operation of the transmission with only frictional coupling. In addition to peripheral slip there is also a so-called radial slip caused by radial and intertooth force. In some types of timing belts, an additional effect on slippage within the support layer has the so-called polygon effect. The tension layer, cord, covers the polygon with the length of the sides equal to the pitch of the belt. This is due to the change of diameters on the arc of the belt which in turn causes a change in the speed of the cord from V min to V max at a constant angular speed ω.

3 The internal friction in timing belt

The most popular materials from which timing belts are made are rubber and polyurethane. Belt manufacturers do not provide details of the chemical composition of the mixtures used. This concern both rubber and polyurethane blends [8]. These materials include rheological processes, creeping, stress relaxation, resilient recurrence, internal friction, dissipation of energy, orientation of the internal structure, permanent deformation. Many studies clearly show the dependence of deformation on stress at repeated loading and unloading of the sample. The size of the hysteresis field and the tilting angle univocally indicate the effect of internal friction and energy dissipation on the mechanical properties of the belts body material. The size of the hysteresis field indicates the amount of energy loss from internal friction. In the case of a rubber material, the largest losses of internal friction energy are noticeable for material not mechanically stabilized for zero load cycles. Therefore, apart from the composition of a rubber mixture, an important treatment is the so-called mechanical stabilization and orientation of the structure, which reduces the energy losses caused by internal friction, increases the mechanical strength of the rubber to tension and untension, and fixes the characteristics of anisotropy. This shows that even when different manufacturers use rubber compositions similar to those used, we obtain a final product with different mechanical and rheological properties [8].

4 Adhesion between the tension layer and the belt's body

Another important feature of the timing belts that affects the quality of the transmission is the connection of the tension layer to the body material. Proper selection of the material of the cord to the belt body material has a decisive influence on the quality of adhesion between the two components of the composite. At the moment, the tension layers in the form of cords

made of steel, stainless steel, aramid, carbon fiber, polyester fiber and glass fiber are used for the production of the belts. The basic materials of the belt's body are polyurethane and various rubber mixtures. Due to the variety of materials, it is necessary to develop a method of calculating the forces occurring in the cord, which will take into account the belt and cord material as accurately as possible. The choice of the right pair of materials has a significant impact, guaranteeing the best adhesion [7]. By using a steel cord in the production of polyurethane belts, we obtain excellent adhesion between the cord and the polyurethane. However, it is not recommended to use such a cord in the case of rubber belts due to insufficient adhesiveness. Another factor that affects the cohesion of the belt with the cord is the type of weave. A cord with the same diameter, but composed of more fibers with a smaller diameter will show better adhesiveness. Some manufacturers use the so-called pre-impregnation to improve the grip of the cord. This method was taken from the tire industry. Similar solutions have been used for years in the technologically demanding tire production process. This treatment consists in covering individual fibers during the braiding process. We get a lot of advantages thanks to it. In addition to the already mentioned improvement in adhesion, the most important improvements include increased corrosion resistance and length stability. This last improvement is due to the increase of the coefficient of friction between individual fibers in the strand, because each one is covered with a polymeric material. Belt manufacturing technology also affects the consistency of the cord with the belt. In case of poor cohesion or incorrect confection, when one strand breaks, the whole belt will break in a short time (Fig. 3). A properly penetrated cord guarantees better properties. In the technology of manufacturing thermosetting polymer belts, the polymer crosslinks for many hours, which in turn creates favorable conditions for the penetration of the cord by polyurethane [7].

Fig. 3. The broken belt with cord pulled out from material

5 Research of energy dissipation in the belt material

For the proper conduct of the energy dissipation test in the running part of the belt, a test stand is prepared. The amount of energy dissipation can be investigated using, for example, a thermovision camera [4]. The test showed significant heating of the pulley teeth. This is due to the fact that there is a friction force when the belt engages on the wheel and from the fact that belt teeth heat up as a result of energy dissipation [9]. Unfortunately, due to the better thermal conductivity of the material from which the pulley is made, the thermovision camera registered mainly the increase in tooth temperature (Fig. 4).
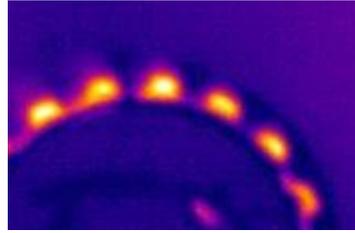
Fig. 4. Dissipating from pulley material

   It shows that the position should be prepared in such a way as to avoid distorting the results. Friction between the teeth of the wheel and the teeth of the belt generates a significant increase in temperature. The better thermal conductivity of the wheel material (steel, aluminum) than, for example, polyurethane will increase the temperature at the surface of the wheels. This situation will seriously disrupt research. Therefore, toothed gears made of material with strong insulating properties should be used to prepare the test stand. This solution will cause that the wheel will not heat up, but it will not reduce the friction and increase the temperature from the friction of the belt teeth on the teeth of the wheel. To minimize friction between the teeth, the belt teeth should be protected during the test by applying an insulating layer, e.g. by spraying a teflon layer. Thanks to this treatment it is possible, using a thermovision camera, to register temperature changes caused by dissipation of energy in the running part of the timing belts.

6 Research of the adhesion between the cord and belt material

To examine the next of the important parameters, namely the amount of adhesion between the cord and the belt material, it is necessary to develop a test bench. This test is carried out on a tensile testing machine. The samples should be properly prepared (Fig. 5) so that it is possible to carry out a cord pull test.

Fig. 5. Samples of belts prepared for testing the cord adhesion

   On the one hand and on the other hand, the sample is attached to a specially designed and made handle. In one holder, the sample is fastened with a clamp. The clamp on one side is smooth and on the other hand toothed. The shape of the teeth corresponds to the type of belt that is being tested. The sample on the other hand is specially prepared, it is devoid of polymer, so that you can grab the sample only for reinforcing cord, using a previously

prepared handle. By using a tensile testing machine it is possible to determine the strength of adhesion between the cord and the belt body. The test should be carried out on the previously assumed number of fibers, which should be the same for each type of belt.

The results of the research showed the dependence of the amount of force needed to pull the cord away from many factors. The basic ones include the diameter of the cord, the number of single wires used in the cord of the same diameter (density of position of wires), cord pre-impregnation, material of the cord and belt body, as well as production technologies.

7 Analysis of friction in timing belt

Over 200 years ago, Euler developed a dependence between the strength of F_1 in the active cord and the force F_2 in the passive cord in case of wrap a weightless, flexible and inextensible thread on a still idler. This dependence is exponential described by the formula (1). Allows to set the limit value of the ratio F_1 / F_2, when the elastic slips cover the entire arc of wrapping. The slip arc has the same size as the arc of wrap. There is no rest arc at all. It can be concluded that the Euler equation refers to the tension layer itself. Taking into account other additional parameters may lead to the extension of the Euler's formula and applying it to calculations for gears with shape-frictional coupling:

$$\frac{F_1}{F_2} = e^{\mu_t \alpha} \, . \tag{1}$$

In the case of transmissions with a synchronous belt, it seems obvious to replace the coefficient of friction with another parameter. During belt operation there is friction between the cord and the body, intermolecular friction and friction between individual fibers in the strand [7]. The amount of friction depends on the body and cord material, the initial impregnation of the cord. The friction between the individual fibers in the strand depends on the fiber material. Whereas, intermolecular friction depends on the fiber material in the case of internal friction in the cord itself, as well as the body material in the case of friction between the polymer molecules. Bearing in mind the above, it is possible to replace the coefficient of friction with a new material coefficient in the case of a timing belt transmission. The Euler's formula makes the dependence between the force in the active belt part and the force in the passive belt part on the static friction between the belt and the wheel and the angle of wrap. The value of the slip in the timing belts depends on the intramolecular internal friction and the adhesion value between the tensioner layer and the body, these two parameters should replace the coefficient of friction used in the formula proposed by Euler:

$$\mu_t = \frac{\mu_1 + \mu_2 + \mu_3}{3} \cdot \theta_i \cdot \theta_k \cdot \theta_w \, , \tag{2}$$

μ_1 – intermolecular friction depending on the type of body material,
μ_2 – friction between cord and body,
μ_3 – friction between fibers in the strand,
Θ_i – impregnation factor, depending on cord pre-impregnation,
Θ_k – length stability factor, depending on the material of the cord,
Θ_w – factor depending on the number of fibers in the strand.

The formula proposed in this way requires support by appropriate research. Therefore, it is necessary to perform a series of measurements, described by the authors. The test results will confirm or deny the validity of the proposed theoretical solution. They will also help to improve the assumption and possibly modify the dependence so that it will be possible to more accurately calculate the relation of F_1 to F_2 for the gears with shape-frictional coupling. The test will determine the amount of force to be applied to the belt cord, to overcome the

force of adhesion and pull the cord from the belt. It is desirable to conduct empirical tests for popular pairs of cord and body materials to develop friction values. The basic cord and body materials include:
- steel fiber - polyurethane,
- kevlar fiber - polyurethane,
- kevlar fiber - rubber compound,
- polyester fiber - rubber compound,
- carbon fiber - rubber compound.

Another study proposed by the authors will allow to determine the value of energy dissipation by measuring the temperature of the toothed part during belt operation. This will allow to determine the amount of internal friction between molecules, which also affects the determination of the amount of elastic slip in the synchronous belt. The type of material, rubber or polyurethane mixture, the degree of crosslinking and the amount of mechanical stabilization and orientation of the polymer chains have an impact on the mechanical quality of the material. Values such as modulus of elasticity, yield stress, Poisson's ratio depend on the atomic and molecular structure of the polymer. Polymers are constructed as a mixture of particle chains, between which there are two types of bonds: main and secondary. The main connect individual atoms in the molecule, while the secondary ones connect individual chains with van der Waals forces. And the strength of the polymer depends largely on the strength of the secondary bonds. The polymer is deformed by shifting individual particle chains. The greater the deformation, the greater the dissipation of energy that causes the local temperature increase. Thanks to the effective measurement in the thermally insulated area of the timing belt, we obtain information on the value of shifts.

8 Summary

The problem of internal slip in synchronous belts is a complex issue requiring further research. This article indicates the direction in which research work should be aimed. The two studies proposed by the authors concern the analysis of phenomena important from the point of view of belt dynamics. Both the cohesion of the carrier layer and the friction within the body material affect the quality of the belt transmission. Proper selection of the tension layer and body materials as well as the correct belt structure guarantees the expected durability of both the belt and the entire transmission. The authors see the need to classify the most popular on the industrial market belts and compare them in terms of the consistency of the cord with the body material and the dissipation of energy in the material of the belt body. The next step should be to compare the results obtained with the empirical method with mathematical calculations. This would allow us to start working on new solutions in the future. Manufacturers of high quality timing belts conduct research similar to those described above, but their results are used for internal studies aimed at improving the quality of belts.

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