Modelling of wear out of timing belt’s pulley

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Abstract. The paper deals with the problem of volumetric wear of timing pulleys. The authors analyze the course of this phenomenon depending on the properties of the belt-pulley friction pair. Timing belts are made of various materials, including additional coating layers, similarly to pulleys. The gear operation problem consists in modeling the pulley life for specific gear materials. The authors made also an attempt to investigate the rate of this phenomenon and its impact on the kinematic efficiency of the transmission gear with timing belts.

1. Introduction
One of the main challenges for contemporary designers is proper design of the entire product life cycle. Therefore, performance tests are becoming more and more important, by which the main part of the product's life is determined – i.e. its operation. Belt transmission gear wear determines its durability and, depending on the type of application, it is longer or shorter than for the system in which it operates. The number of belt and pulley replacements need to be designed [1, 2]. Thanks to performance tests it is possible to determine proper durability, which should characterize a properly designed transmission gear in line with the expectations of users. Currently, legal regulations such as the 24-month guarantee and other system safety-related requirements result in the introduction of quantities that allow determining the proper life of the belt transmission gear [3, 4]. Those quantities are not comparable between each other and between individual transmission gears, but it is assumed that the proper life amounts to 6 thousand hours of the transmission gear operation or 10 million belt operation cycles, or 6 years, and in the case of passenger cars, their mileage is specified. Currently, a high-quality belt is replaced once a car reaches the mileage of 300 000 kilometres.

2. Materials used in production of timing belts
A modern toothed belt is made of a cord, belt material and fabric coating. The shape and the arrangement of the teeth over the width of the belt have not changed for over ten years. The last significant solution introduced included helical toothed belts. The internal structure has been similar for decades and efforts have been made for many years to develop belts characterized by mechanical properties not worse than those of a chain, while their main advantage has been lower noise emission [5–7]. Significant technological progress in material engineering has allowed the production of belts the properties of which are ahead of chains. They enable transfer of higher powers, achieve higher linear speeds, are more durable and do not require supervision and lubrication [8, 9].

The materials used in the production of toothed belts are similar to those used in car tires, which is why, at their early stages, toothed belts were produced by almost all tire manufacturers (figure 1). The
main material of a belt has always been synthetic or natural polymer, while the reinforcement in the form of a cord has been made of steel, Kevlar, Aramid or other fibres. The belt's surface was usually covered with an elastic polyester fabric reducing the friction of the belt against pulleys. The revolution in toothed belt materials occurred in all areas. Modern polymer blends of higher resistance to mechanical stress have been developed [10, 11]. As regards the cord, new strands have been developed and the quality of materials has been improved, and high-quality carbon fibres called CARBON have been introduced. Coating fabrics are made of state-of-the-art polyester materials filled with PTFE, which significantly reduces the belt-pulley friction coefficient thus reducing the belt's volumetric wear.

Figure 1. PU material "Vulcolan"-aging result: a) one year, b) tree years, c) six years.

3. Materials used for the production of pulleys

High quality of modern toothed belts induces the search for suitable pulley materials such that the longest possible operation time is ensured by the pulley-belt friction pair. Pulleys made of cast iron, steel, aluminium alloys, polyethylene, acetal, etc. have often been used in existing design solutions [12–14]. When working in tandem with high quality toothed belts, they can be worn faster than the belt (figure 2). One of the parameters allowing to determine the wear rate is the friction coefficient. The expectations to date have revealed the need to reduce this parameter. Lower friction means reduction in the meshing temperature, which limits the migration of pulley particles to the belt. Another parameter is the hardness of the pulley material. Harder material prevents the migration of belt, dust and dirt particles from the environment to the pulley surface [15, 16].

Experiences in the area of abrasion resistance indicate that the best solution for surface abrasion resistance is the pulley surface hardening. The inner material itself does not have to be hard.

Figure 2. Timing belt pulley made from aluminium alloy over used, wear on one side.
4. Timing belt wear out

Belt transmission gear wear can be characterized by four basic phenomena: aging of belt material, energy-related wear of polymer, volumetric wear – abrasion of transmission gear components, and fatigue, which applies to crystalline materials, cord and pulleys. The aging processes consist in the degradation of the polymeric material properties, and that applies, to a greater or lesser degree, to all materials used in the production of belts. Thermoplastic materials exhibit better properties than thermosetting materials in this respect. It is possible to add special additives to polymer blends that delay degradation process, but it should be emphasized that duroplasts are characterized by the best properties immediately after the vulcanization process and the properties deteriorate over time. This can be observed because the appearance of their surface changes, i.e. the colour often changes significantly, they become very brittle, which completely excludes them from further use [17, 18]. This results from decaying energy of bonding between polymer molecules, changes inside polymer chains caused by the exchange of energy with the environment, etc. It is these processes that determine the maximum length of storage period of such belts in dark warehouse conditions at room temperature to be 6 years. The phenomenon of polymer energy-related wear is associated with frequent and excessive strain of the belt material. As a result, the properties of the belt material change and accelerated aging occurs. Micro-cracks are formed in the belt material, which then transform into cracks and defects of the material. The parameter expressed in the form of the number of belt cycles is associated with this phenomenon. "Long" belts perform fewer cycles when running on pulleys moving at the same speed as short belts. "Short" belts are frequently bent, loaded and unloaded. The same applies to their teeth.

A very similar phenomenon is material fatigue, which concerns the weakening of intermolecular forces in crystalline materials due to frequent load variations. The fatigue process in toothed belt transmission gears occurs concurrently with the energy-related wear of the polymer [19, 20].

The most frequently and most easily observed wear phenomenon is the volumetric wear of toothed belt transmission gear elements (figure 3).

![Figure 3. Timing belt’s running side, wear out up to cord level.](image)

5. Modelling of pulley wear out

Modelling of the pulley wear out is important to determine of the speed of its wear and thus the durability of the entire transmission. To develop the model, it is necessary to determine the reasons and types of wear of the wheels and timing belts. In model of wear out the basic issue is the selection of types and materials of associated belts and wheels. Research on pulleys has demonstrated that the volumetric wear of a pulley teeth is a predominant wear type (figure 4). Depending on the belt and pulley wear degree, the wear occurs in the following sequence: sides of the teeth, the tips of the teeth and then inside the tooth root [21, 22].
Figure 4. Measurement on microscope overused pulley.

The partial wear of the pulley race, as shown in the figure, is caused by the belt running on one side of the race. The transition between the worn and unworn side is another factor allowing modelling of the wear process. The durability $D$ of a gear with timing belt depends on the coupling quality in the transmission [2, 3]:

$$D = \frac{S_1}{S_2} = f(\sigma_k, \sigma_p, K_W, A_{kp}, Y, Z)$$  \hspace{1cm} (1)

where: $K_W$ – belt pitch utilization factor, $\sigma_k$ – cord deformation (extension and twist), $\sigma_p$ – belt material deformation causing belt tooth height change $\sigma_{ph}$ and the width change $\sigma_{pb}$ as well as shape change $\sigma_{pA}$, $A_{kp}$ – adhesion factor for cord, belt material and additional materials, $Y$ – the toothed belt pitch to toothed pulley pitch ratio, $Z$ – belt and pulley wear of volumetric $Z_v$ and energetic $Z_e$ type:

$$\sigma_p = \{\sigma_{ph}, \sigma_{pb}, \sigma_{pA}\}$$  \hspace{1cm} (2)

$$Z = Z_v + Z_e$$  \hspace{1cm} (3)

The pulley surface hardness problem was addressed in studies which compared the surface wear of the pulleys made of various materials and additionally hardened. The choice of belt designs and wheels for belt transmission is to achieve durability of min. 6 000 hours (figure 5).
Figure 5. Scanning of pulley from two sides.

The wheel on which the belt worked on one side was tested. The results showed a clear loss of wheel surface geometry. Pulley in such technical condition should be removed from service, because the belt working on such surface will be destroyed very quickly.

Further tests were carried out for wheels made of various aluminium alloys. The belt worked on wheels to carry a nominal load of 6 000 hours. The drawings show much higher volumetric wear of alloy wheels with the addition of Zn (figure 6).
6. Conclusion
The studies have shown that proper selection of belt-pulley friction pair material quality is important for the durability of a toothed belt transmission gear. Belts coated with high quality laminate can have higher abrasion resistance than pulleys. Therefore, the toothed pulleys of toothed belt drives must be very hard or undergo special hardening treatment. It should be emphasized that choosing the right pulley material for the transmission design is as important, as proper choosing of the belt material. Only with knowledge about these materials can by propose, a model of working and durability of a toothed belt transmission.

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