Increasing the operational reliability of car variators due to creating regular surface microrelief by laser ablation

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Abstract. The paper analyzes the car variator reliability issue. The variator performance is ensured by the surface layer quality, manufacturing accuracy, and the pulley and steel V-belt surface microrelief. The decisive factor in ensuring the variator reliability is the pulley finishing technique. Creating regular microreliefs on the finished pulley surface by laser ablation has been proposed, which act as micro-channels to improve the drainage of oil from the contact pattern. Creating oil channels on the pulley surface by laser ablation will ensure their arrangement and allow obtaining the desired pattern, direction, depth, and length.

1. Introduction

The progress and development of the motor vehicle industry are constantly ongoing; earlier, the car manufacturer, engine type, and vehicle class have been the key factors when choosing a car. Currently, when buying a car, one of the decisive factors is the type of gearbox installed. There are four transmission types used worldwide:

- Manual (MGB);
- Automatic (AGB);
- Semi-automatic (SAGB);
- Variable-speed (Variator, CVT).

Most buyers choose cars with an automatic, semi-automatic, or variable-speed gearbox. This is because they show better behavior and greater comfort compared to a manual gearbox. Both automatic or semi-automatic and variable-speed gearboxes have advantages and disadvantages. A significant advantage of variators is the continuously variable gear ratio, which allows leveraging the engine traction capabilities and its optimal operation, and great fuel saving.

The globally accepted abbreviation for variator is CVT (English: continuously variable transmission). The main disadvantage of variators is a rather low operational reliability. Let us analyze the reason for the variator reliability decrease and propose solutions to improve it.

Variable-speed gearbox CVT consists of two adjustable cone pulleys and a steel V-belt (Figure. 1) [1]. Since the cones of each pair of the pulleys move relative to each other, their conical shape causes the belt to go up and down between the pulley grooves. The active gear ratio varies depending on the belt position in each pulley. The CVT gearbox pulleys create a continuous exchange of gear ratios by
constantly changing the belt position between them. This provides a limited range of gear ratios according to the pulley diameters, and all gear ratio values are available within this range.

Figure 1. Diagram of a Variator with Adjustable Cone Pulleys: 1 – drive adjustable pulley; 2 - slave adjustable pulley; 3 - steel V-belt.

Torque is transmitted due to friction between the pulleys and the side surface of a steel V-belt. This design ensures high strength, durability, flexibility, and low noise during operation (Figure. 2) [2-3].

Figure 2. CVT Assembly: Two Pulleys and a Belt.

The variable-speed gearbox reliability depends on the life of the main CVT unit – the pulley-belt friction pair. In the course of operation, torque is transmitted due to friction between the pulley-belt contact pair. The special CVTF (Continuously Variable Transmission Fluid) affects the provision of the required coefficient of friction.
The development of a steel V-belt (Figure 3) consisting of 10-14 layers of 0.2 mm thick steel strips made of maraging steel 18Ni16.5Co5Mo and numerous segments strung on them has ensured transmitting torque up to 180 Nm and allowed widely using variators in cars [4].

![Figure 3. Steel V-belt [4].](image)

The paper's objective is the possibility of creating regular microrelief on the pulley-belt friction pair surfaces by laser ablation to increase the variator reliability.

2. Materials and methods

In the variator, torque is transmitted from the drive pulley to the slave one due to friction between the steel belt and the pulleys. To create the required friction force between the belt and the pulley, the belt is tensioned with a preliminary tension $F_0$. (Figure. 4). At rest and when idle, each belt branch is tensioned with the same force $F_0$.

When a car starts moving at an operating load $T_1$, the tension is redistributed between the belt branches. The leading branch is additionally loaded to $F_1$ value, and the slave branch is released to $F_2$ value [1].

![Figure 4. The Belt Forces.](image)

From the condition of the external moment balance about the rotation axis, we have:
\[-T_1 + \frac{F_1 D_1}{2} - \frac{F_2 D_2}{2} = 0.\]  \hspace{1cm} (1)

Since \( T_1 = \frac{F D_1}{2} \), then from equation (1) we obtain

\[ F_1 - F_2 = F_r. \]  \hspace{1cm} (2)

The total belt length remains unchanged during operation since the leading branch elongation is compensated by an equal contraction of the slave branch. It means that whatever extent the slave branch tension increases to that extent the driven branch tension reduces, i.e.

\[ F_1 = F_0 + \Delta F, \quad F_2 = F_0 - \Delta F. \]  \hspace{1cm} (3)

When adding the equations, we obtain:

\[ F_1 + F_2 = 2F_0. \]  \hspace{1cm} (4)

When solving equations (1) and (4) together, we obtain

\[ F_1 = F_0 + 0.5F_r, \]  \hspace{1cm} (5)

\[ F_2 = F_0 - 0.5F_r. \]  \hspace{1cm} (6)

Equations (5) and (6) describe the changes in the leading and slave branch tension depending on the load \( F_t \) but do not consider the friction force between the belt and the pulley. Since the creep occurs throughout the entire wrap, then the dependence between \( F_1 \) and \( F_2 \) is expressed by the Euler’s formula.

\[ F_1 = F_2 e^{f\alpha}. \]  \hspace{1cm} (7)

Equation (7) describes a relation between the branch tension forces for a gear operating at the load \( F_t \), the friction coefficient \( f \), and the wrap angle \( \alpha \). This allows determining the minimum belt pretension \( F_0 \) required, at which the transmission of a given load \( F_t \) is still possible.

If \( F_0 \ll \frac{F_t}{2} \left( \frac{e^{f\alpha} + 1}{e^{f\alpha} - 1} \right) \), then the belt will creep.

The analysis of the above dependences shows that an increase in the \( f \) and \( \alpha \) values allows increasing the torque transmitted and consequently improves the variator reliability.

These conclusions will be treated as the main way to improve the variator reliability using the principle of increasing the pulley-belt friction. Reduced wear of the contact surfaces depends on the precision of manufacture and the pulley and metal V-belt surface microreliefs.

The studies on the pulley-belt friction pair reliability are most often aimed at improving the V-belt design [4]. Using belts of improved design or those made of new materials does not completely solve the issue.

When manufacturing and repairing pulleys, special requirements for the contact area of the pulley-belt friction pair are not being considered. The processing type and the pulley surface microrelief may contribute to both increasing and reducing the friction coefficient.
3. Result and discussion
The technology proposed is based on creating a guaranteed microrelief on the pulley-belt friction pair surface ensuring the required frictional properties and wear resistance of parts [5, 6]. The performance and reliability of the pulley-belt friction pair can be improved by creating regular microreliefs on the finished surface, which act as micropumps [7].

Grooves placed at a negative angle of inclination $\gamma$ clockwise from the rotational velocity vector will act as micropumps draining liquid out of the cavity. The pulley-belt friction pair operation can be controlled by changing the depth and density of grooves.

Processes for obtaining partially regular microreliefs and completely regular relief have been considered in [7]. After grinding, the surface microrelief is a chaotic pattern of micro bulges and micro dents of various configurations and depths.

After finishing by grinding, on the pulley surface, annular grooves have formed (Figure. 5a) that increase the oil-absorption power of the surface and lead to deterioration of the contact pattern of the belt-pulley friction pair. During operation, it contributes to belt slip and scoring (Figure. 5b). Conventional techniques available do not allow arranging the micro bulges and micro dents to obtain the required oil channel pattern.

![Figure 5. CVT Pulley a) after grinding, b) with scoring during operation.](image)

A model of the existing and proposed microrelief structure of the pulley-belt friction pair surface is shown in Figure. 6.

In recent years, the development of nano-, pico-, and femtosecond diode-pumped solid-state lasers has led to a quantum leap in the creation of new cutting techniques [8–14]. The use of short-pulsed lasers has ensured such a power density in the processed area at which the substance evaporates, and laser ablation occurs.

Various laser cutting, drilling, and milling processes have been developed based on diode-pumped lasers generating nanosecond pulses.

The power density of the laser radiation incident on the processed surface with a reflection coefficient $R(\lambda)$ at the given area and duration of exposure can be approximately estimated by the below equation [9]:

$$W = \frac{(1 - R)E_i}{S \cdot t_i},$$

where $R$ is the reflection coefficient of the material processed at the radiation wavelength, $E_i$ is the pulse energy in Joules, $S$ is the radiation incident surface area in cm$^2$, and $t_i$ is the pulse duration in...
seconds. Depending on the processing type and the properties of the material processed, to obtain the required power density on the sample surface, laser radiation of a certain power with a given pulse duration should be applied.

Figure 6. The Pulley-Belt Friction Pair Microrelief Model.  
a) existing surface structure  b) proposed surface structure.

According to the zone map of typical laser processing, the heat strengthening is performed within the interval \( W = 10^5 \text{--} 5 \times 10^6 \text{ W/cm}^2 \). Within the range \( W = 5 \times 10^5 \text{--} 5 \times 10^6 \text{ W/cm}^2 \), the temperature reaches a level suitable for surfacing and welding of metals. At a laser power density of \( W > 5 \times 10^6 \text{ W/cm}^2 \), laser ablation allows drilling, cutting, and milling various materials. Precision laser processing is based on drilling, cutting, and milling.

The laser ablation unit based on diode-pumped laser generating nanosecond pulses is shown in Figure 7. This unit is equipped with a laser, a precision rotary positioning stage, an optical radiation focusing system, and an automated processing control and monitoring system.

Figure 7. Experimental Laser Ablation Unit, Ytterbium Fibre Laser IPG Photonics, 1.064 μm Operating Wavelength.
4. Conclusion

(1) The research results have shown that existing conventional techniques do not allow obtaining an arranged microrelief of oil channels with the pattern required.

(2) After finishing by grinding, on the pulley surface, annular grooves have formed that increase the oil-absorption power of the surface and lead to deterioration of the contact pattern of the belt-pulley friction pair.

(3) The use of laser ablation technique allows obtaining the required microrelief on the variator pulley surface, ensures high-quality processing and high accuracy of the geometric pattern of the structures processed.

(4) The variator reliability can be improved through the formation of regular microreliefs by laser ablation.

5. References

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