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EXPERIMENTAL COMPARISON OF WEAR RESISTANCE AND CYCLIC LOADING TO BENDING BETWEEN CYCLOID AND INVOLUTE GEARS

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Abstract: *The reasoning for the proposed replacement of involute gears with cycloid is given. The experimental results obtained from comparative tests between cycloid and involute plastic gears in terms of load capacity, wear resistance, temperature on pitch point and noise emission are reported. Some conclusions with respect of the derived experimental results are made.*

Key words: *cycloid gears, involute gears, plastic spur gears, wear, pitch line fracture*

1. Introduction

The use of plastic gears is already widely spread in many industries and applications, which is on account of their beneficial properties – low cost; light weight and low inertia; capability to absorb shock and vibration; noiselessness; their tolerances often less critical in comparison of metal gears; their ability to operate under dry (not lubricated) conditions; etc. [1]. However, when using plastic gears (comparatively with metal gears) should be taken into account such their shortcomings as lower strength parameters concerning broken teeth from bending fatigue, greater wear and lower contact resistance of the tooth flanks, greater thermal expansion and contraction, greater absorption moisture, etc.

Up to now a lot of investigations are made to improve load capacity and durability to wear of the plastic gears. For improving the capacity to cyclic loading of the plastic gears are used different measures – appropriate choice of a module, pressure angle or number of teeth [2]. These measures have controversial effect, which effect depends by the type of the plastic - hard thermoplastic or elastic thermoplastic. Another approach is, for example, the use of advanced plastics or reinforced plastics with appropriate fillers (carbon or glass fiber) - but this is linked to increased costs of the final product. The latter approach is used successfully to improve the durability to the wear [3]. And other techniques are used to improve durability against wear of gears - Rao et al [4] looked at the effect of poly-tetra-fluoro-ethylene (PTFE) as an internal lubricant on the friction and wear of filled and unfilled PA66 and polyacetal; Akkurt [5] examined the effect of the surface roughness of steel gears running against polymer (acetal) gears; by K.D.Dearn, T.J.Hoskins, D.G.Petrov et al [6] have investigated the possibilities of using a series of solid lubricant coatings deposited on flanks of the polymer gear teeth.

Stanislav Aleksiev et all [7] have proposed substitution of the involute profile of teeth with cycloid profile for plastic gears to improve the load capacity and the durability to wear and have made an attempt to justify theoretically, in their opinion, the advantages of cycloid profile in comparison with the involute profile. For this purpose, two gear pairs with two identical spur gears with number of teeth z=17 and module m=1 mm are theoretically compared - one gear pair with involute profile and the other - with cycloid profile. Here is found by simple calculating, that the sliding velocity between meshing teeth profiles in the case of using of cycloid profiles is less than the case of using of involute profiles. The second reason for less wear of the cycloid gears is the presence of smaller contact stresses in comparison with the such contact stresses of involute gears, because of fact that in the cycloid gears the contact take place between a convex flank and concave surface, whereas in involute gears, the convex surfaces are in contact [7, 8]. In [7] it is further maintained that the teeth's strength against bending in the cycloid gears will be greater than that of the involute gears, due to thicker root at the base of the tooth.

The purpose of this work is to report about the experimental results derived in the comparative tests in respect of load capacity and resistance to wear of plastic spur gear wheels - the half of plastic spur gear wheels are made with cycloid profile of the teeth, the second half are made with involute profile. These comparative tests have been made to ascertain experimentally the correctness of the suppositions given in [7].

2. Materials and basic parameters of the gear wheels, test rig, experimental methodology and conditions

All the studied plastic spur gears were made by typical for that purpose material polyamide PA 6. The target applications of that material are transportation, mechanical engineering, automotive industry, conveyor technology, packaging and paper machinery, textile industry. Because of its main features as high strength, good slide and wear properties, good machinability, resistance to many oils, greases and fuels, low cost, it is widely used for manufacturing of gears. The main mechanical properties (as density 1.19 g/cm^3, ball indentation hardness - 175 MPa (at norm ISO 2039-1), modulus of elasticity (tensile test) - 3900 MPa (at norm DIN EN ISO 527-2), tensile strength - 79 MPa (at norm DIN EN ISO 527-2), impact strength (Charpy) - 53 kJ/m2 (at norm DIN EN ISO 179-1eU)) and thermal properties (melting temperature - +221°C (at norm DIN 53765), long term service temperature - +100°C, short term service temperature - +160 °C) of polyamide PA 6 could be found in [14].

The studied plastic spur gears were made by means of cutting – four involute gears (fig.1) were made on hobbing milling machine (machining with hob cutter), and four cycloid gears were made on CNC milling machine by means of end milling cutter. Except their profile, all the gears have steel insertion (fig.2) and similar parameters - number of teeth z = 15, module m = 4 mm, width of the tooth crown b = 18 mm, profile angle of pitch circle α_w = 20°.

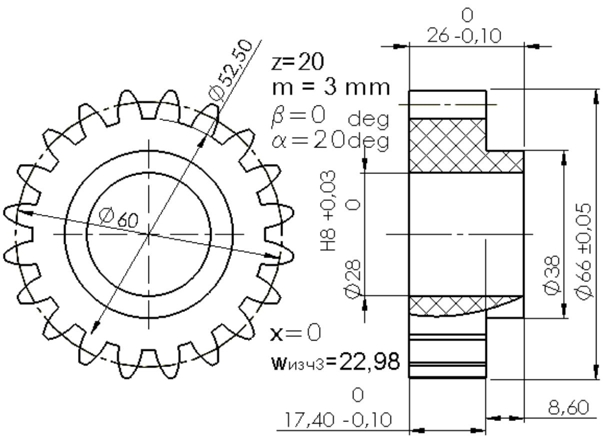

Fig. 1. *Sketch of plastic gears.*

The photo of the test rig used for the tests and its scheme are shown on fig.3 and fig.4. It is a closed loop rig designed specifically for testing polymer gears and is described in [9, 10]. One gearbox (Master Gearbox) contains identical metal gears, which do not require replacement, while the polymer test gear pair forms the opposing set. The power to drive the arrangement is that which is needed to overcome the gear sliding and bearing losses in the system. When the motor is switched on the reactive forces between the test gears balance the externally applied torque and the bearing block and loading arm are maintained in balance. When using a closed loop system the torque is normally wound-in but for plastic gears wear and tooth deformations would mean that the torque would change (reduce) with time. Using a pivot block and load arm to load the gears ensured that the test gears were subjected to a constant load throughout the test. As the test gear wear, the bearing block rotates about the pivot. Quite large rotations are allowed, and, because of this and the associated differential movement, the closed loop drive shafts are free to slide axially and are fitted with universal joints.

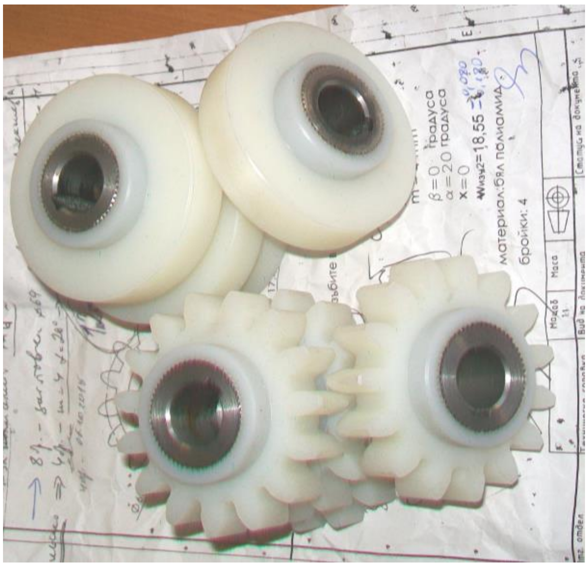

Fig. 2. *Plastic gears with steel insertion.*

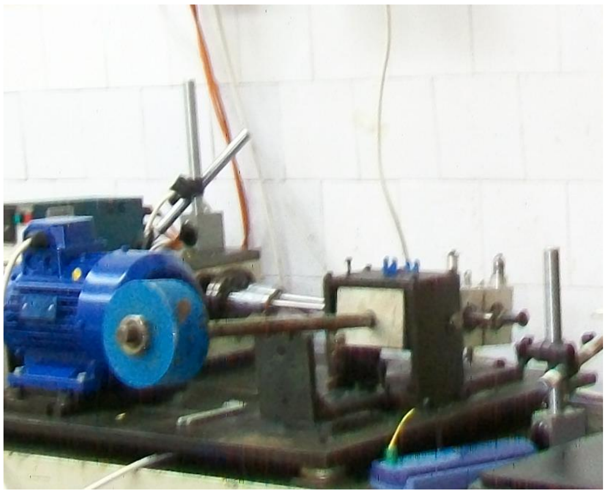

Fig. 3. *Photo of the test rig.*

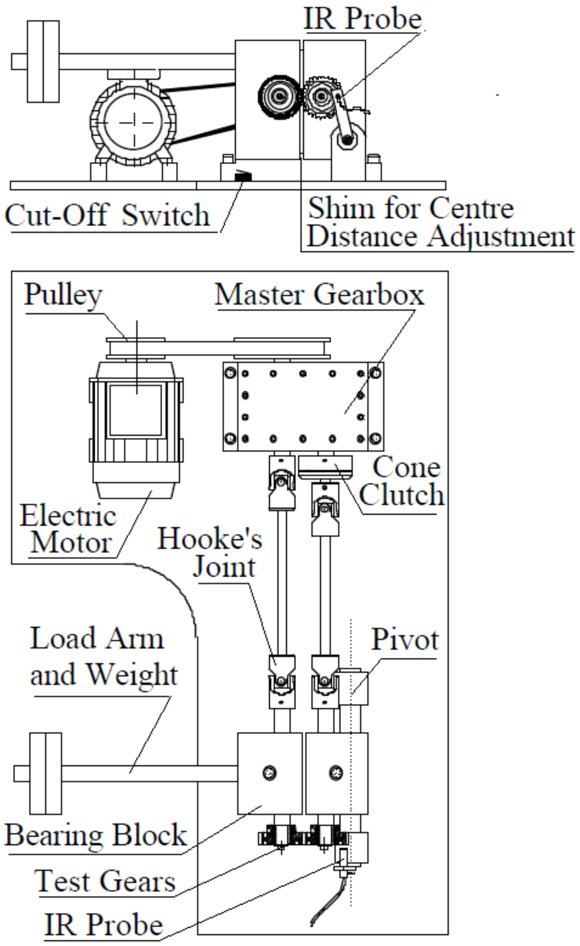

***Fig. 4.** The scheme of the test rig.*

Two pairs of gears (one with involute gears and the other with the cycloid gears) were tested to ultimate load (calculated for involute gears for 1500 load cycles) of 25,2 Nm, and similar other two pairs of gears were tested at lower load of 18,9 Nm for testing of wear resistance. The tests were conducted at dry running (without lubrication) and at 1000 rev/min^{-1}. Wear of the test gears was measured by mass loss using an electronic precise analytical balance [15] - model TP-214 (weighting capacity - 210 g, readability - 0,1 mg, repeatability - ≤ 0,1 mg, linearity - ≤ 0,2 mg). To do this the meshing gears were stopped periodically, (noting their relative positions), then removed and after weighing they were replaced as closely as possible to the original positions. To account for changes in moisture content of the test gears, the mass of a control gear, mounted on the pivot block assembly during running, was measured at the same time as the test gears. Relative wear (as a percentage mass loss, *R%*) was calculated using equation(1)

$$R\%_i = \frac{\left(\frac{Q_i}{Q_0}.P_0 - P_i\right)}{P_0}.100\% \qquad (1)$$

Where: P_0 - original gear mass; P_i – current gear mass; Q_0 - original control gear mass; Q_i - current control gear mass; $R\%_i$ – current relative mass loss.

The temperature at the pitch point of the gears was continuously measured using non-contacting infra-red thermocouple and the data stored on a computer. In such non-contacting manner was measured the noise from tested running gears (with portable sound-level meter GM1351 – measuring range: 30 – 130 dB; accuracy: ±1.5dB (94dB at 1kHz); frequency response: 31.5Hz-8.5kHz).

3. Experimental results

Fig.5 shows the relative loss of mass (the relative wear) against the number of cycles for the four tested polyamide gears – two pairs of cycloid gears and another two pairs of involute gears (respectively from each type of gears (involute and cycloid) the one pair loaded with 25,2 Nm and the other pair loaded with of 18,9 Nm). Note that each point on the graphs represents the average of relative mass losses of the drive gear and the driven gear that have been measured simultaneously after given number of cycles. The sharp jumps at the end of the curves for greater load of 25,2 Nm correspond to the fracture of one and then of a second tooth of the drive gear in each gears pair - involute and cycloid.

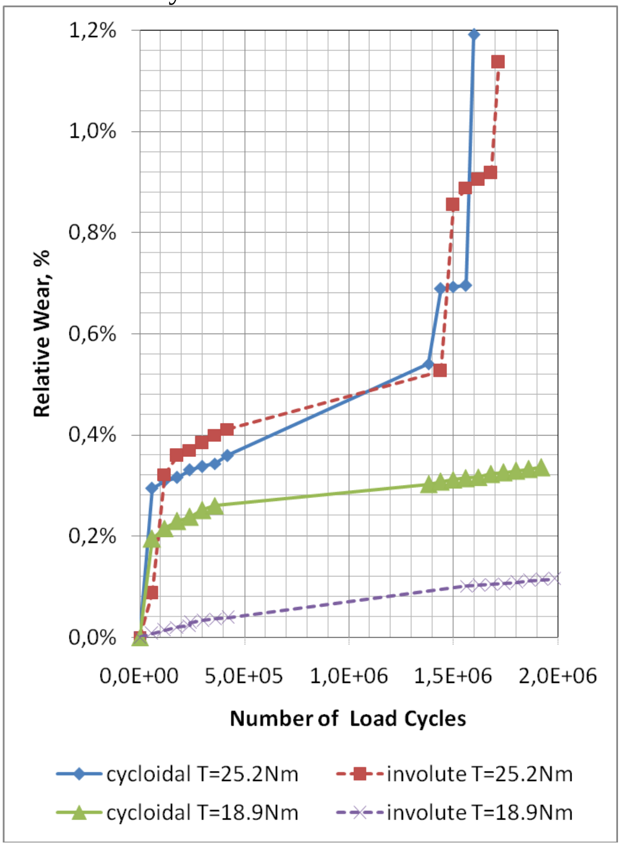

***Fig. 5.** Relative Wear, % - load cycles.*

It could be seen that there are not big differences in curves for loading with 25,2 Nm – the behaviors of the cycloid gears and involute gears are identical. Both gears suffered fractures of teeth after approximately $1{,}5\times10^6$ cycles. On the other hand, in the case of lower (of 18,9 Nm) load, involute gear showed less wear over the time than the cycloid gear.

The fractures of teeth in both cases of (involute and cycloid) gears occurred on the drive gear, not on driven gear and in addition of that they occurred higher on the tooth, not on the root of the tooth. The fractures on the drive involute gear wheel happened near the pitch circle (Fig.6), on the drive cycloid gear wheel happened little lower (Fig.7) and they for both had fatigue nature (Fig.8).

Fig. 6. *Pitch line fractures for involute gear.*

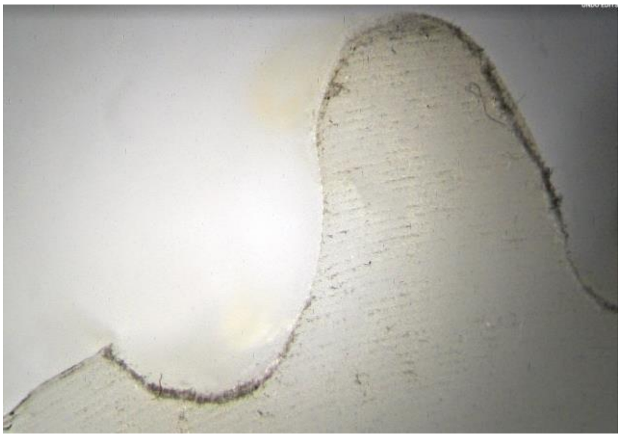

Fig. 7. *Fracture and wear on cycloid gear wheel.*

In our opinion the causes for breaking teeth on drive gear wheels are complex – excessive wear, pitting, cracking at pitch circle (fig.9). Sliding forces always act away from the pitch point on the drive gear and towards the pitch point on the driven gear. So, sliding forces (fig.10) make wear and in addition push material away from the pitch point on the driving tooth (a), leaving a small pit or push material towards the pitch point on the driven leaving a small tip (b) [11,12]. This pit is the most probably the cause (concentrator of stresses) for cracking and breaking tooth on pitch line (so-called “pitch line fracture” [12]) for drive gear.

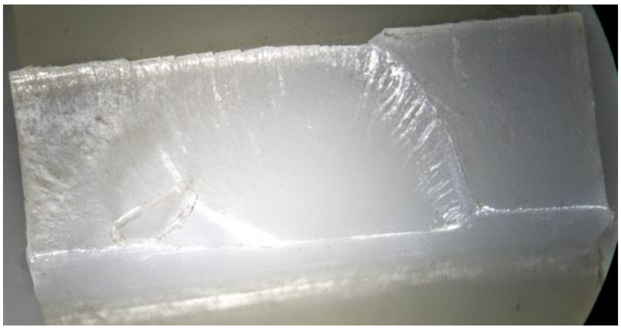

Fig. 8. *Pitch line fracture with a fatigue character of a tooth for involute gear.*

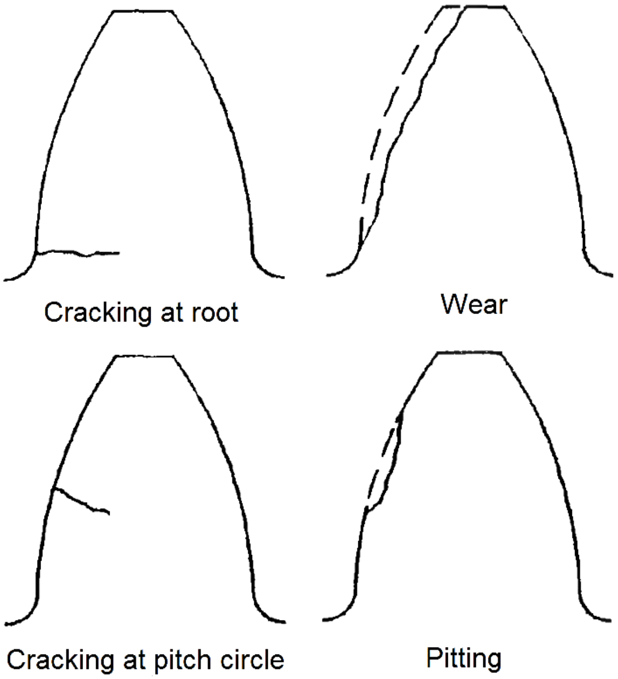

Fig. 9. *Modes of failure that commonly occur in plastic gears – after Walton D. & Shi Y. W.[13].*

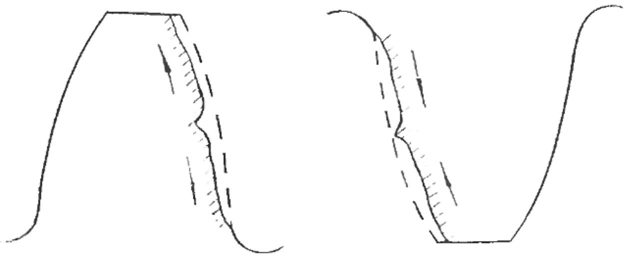

Fig. 10. *Wear profiles on plastic gear flanks for (a) the driver and (b) the driven gears.*

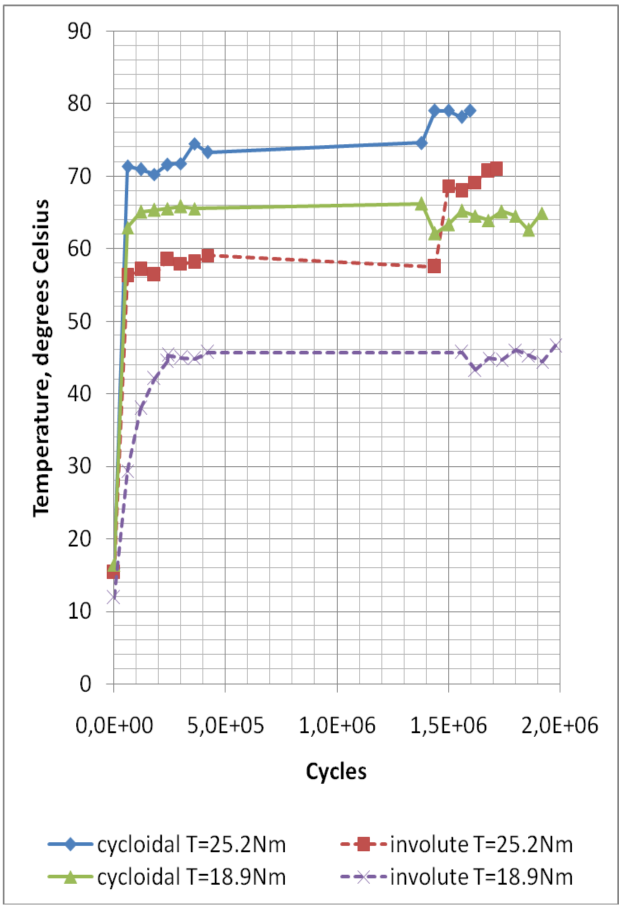

Fig. 11. *Temperature curves.*

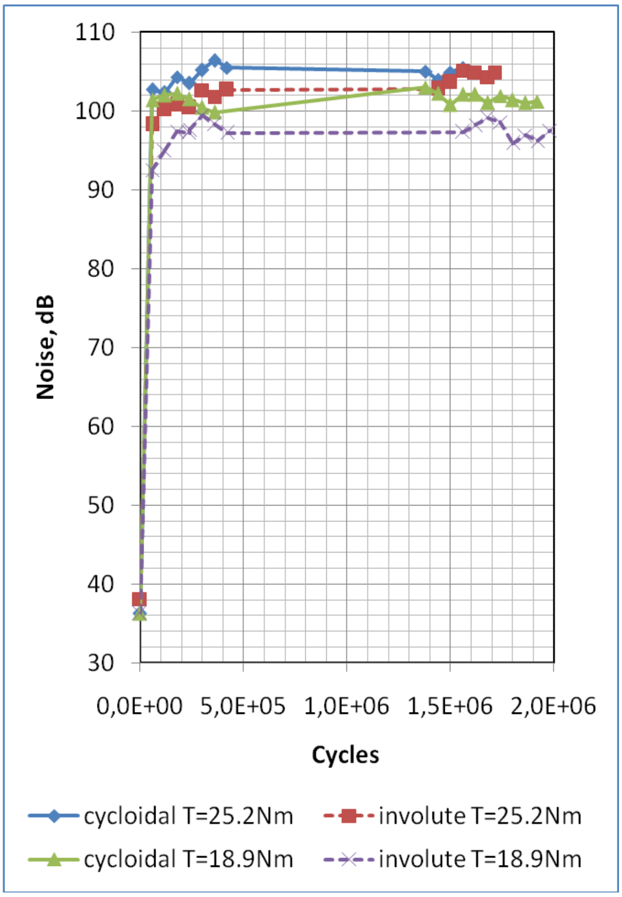

Fig. 12. *Noise curves.*

On fig. 11 and fig.12 are shown the curves of all four gears for measured temperature on pitch point and for measured noise from gears. Again the involute gears had better performance than cycloid – with lower temperature and noise emissions.

4. Conclusion

Contrary to the assumptions in [7], experimental results derived by us did not prove the expectations about greater long-term resistance to wear and against cyclic loading of the cycloid gears in comparison of involute gears.

In the extreme test the cycloid gear suffered breaking of teeth a little earlier than the corresponding involute gear, while in the lighter test the cycloid gear showed more wear than the involute gear did.

This was confirmed and by the results of measuring the temperature at pitch point and the noise emission. In the our experimental tests, the cycloid gears have showed emissions of more heat as well as of more noise, which was an indirect evidence of a presence of more intense wear and of more vibrations causing noise with sound frequencies.

These results can be explained by the fact that the work of cycloid gears is more dependent of the accuracy of their manufacturing and much more sensitive to the observance of the exactness of center distance, than the same is for the involute gear drives.

The observed from us fractures of teeth near the pitch circle are specific and characteristic to the plastic gears. The reason for their (of pitch line fractures) occurrence is still unclear and is the subject of research. In our opinion, the appearance of these fractures in the vicinity of the pitch circle is due to the formation of a typical groove (fig.10) under the effect of the sliding forces and in the absence of lubrication on the flanks of the teeth of the drive gear. This groove (fig.13) is a concentrator of stresses - here begins the appearance of cracks at the line near the pitch circle ending with a fracture of the tooth.

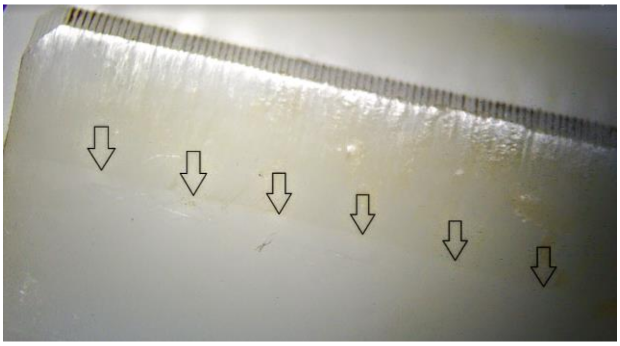

Fig. 13. *Furrow on the flank of tooth of drive gear.*

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REFERENCES

1. http://plastics.dupont.com/plastics/pdflit/americas/markets/*gears*.pdf.
2. Rudy Walter, (2004), *Engineering Principles for Plastic Gears*, Gear Solutions, gearsolutionsonline.com, pp 24 - 35
3. H. Voss and K. Friedrich., (1987), On the wear behaviour of short-fibre-refinforced PEEK composites. *Wear* 116, pp 1-8,
4. M. Rao, C. J. Hooke, S. N. Kukureka, P. Liao and Y. K. Chen, (1998), The effect of PTFE on the friction and wear behaviour of polymers in rolling-sliding contact. *Polymer Engineering and Science*, Vol. 38, No. 12, pp 1946-1958.
5. S. Akkurt, (1995), On the effect of surface roughness on wear of acetal-metal gear pairs. *Wear* 184, pp 107-109
6. K.D.Dearn, T.J.Hoskins, D.G.Petrov, S.C.Reynolds, R.Banks,(2013), Applications of dry film lubricants for polymer gears, *Wear*, Volumes 298–299,2 15 February 2013, Published by Elsevier B.V., Pages 99–108
7. Stanislav Aleksiev, Miroslav Aleksiev, Theoretical justification for the selection of curves engage manufacturing of gears from polymer material, *Tribological Journal BULTRIB* (Volume V, Number 05 (05) 2015), ISSN: 1313-9878, Printing House of the Technical University, Sofia, Bulgaria, pp 291-295 (in Bulgarian).
8. R.S. Khurmi & J.k. Ghupta, (2005), A Textbook of Machine Design (S.I. Unit), Eurasia Publishing House (PVT.) LTD., Ram Nagar, New Delhi – 110 055, pp 1031-1032.
9. Mao K., (1993), *The performance of dry running non-metallic gears*. PhD thesis, Birmingham University, pages 52-66.
10. A.B.Cropper, (2003), *The failure mode analysis of plastic gears*, PhD thesis, Birmingham University, pages 233-260.
11. Tsukamoto N, (1979), Investigation about the strength of plastic gears, 1st report; the strength of nylon gears which have counter-crowning, *Bulletin of JSME*, Nov, Vol.22, No 173.
12. White John,(1998),*The design and evaluation of polymer composite spur gears*, PhD thesis, Birmingham University, pages 52-66.
13. Walton D, Shi Y.W., (1989), A comparison of ratings for plastic gears, Proc. IMechE Part C: *Journal of mechanical engineering science*, Vol. 203, pp. 31-38.
14. http://www.ensinger-online.com/my/materials/engineering-plastics/polyamides/#c49084
15. http://www.denverinstrumentusa.com/media/pdf/Op-Man-Timberline-Series-balances.pdf

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