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A NEW METHOD OF CHOOSING GEAR WHEEL MATERIALS

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***Abstract**. This thesis paper presents a rational method of choosing pinion and driven wheel material, based on the principle of choosing the cheapest material on condition that it meets all basic technical requirements imposed.*

***Key words:** materials, gear, method of choosing, pinion, driven wheel.*

1. INTRODUCTION

In design, the choice of materials for the drive gear wheel and the driven gear wheel represents a vital problem that can only be solved rationally by optimisation. Nevertheless, standards and even literature in the field point that the methods are more important than the choice of materials [6] [7].
For a certain case of actual usage, the materials of gear wheels determine to a great extent the size, shape, execution technology and functioning time of the whole gear or the compound train of gears. It is this aspect that renders the choice of materials and heat treatments so important.

2. PRINCIPLES IN CHOOSING THE MATERIAL AND THE TREATMENT OF THE PINION

The choice of materials and heat treatments for the pinion and the driven gear wheel of each gear is done at the completion of an analysis that presupposes a preselection stage, during which the group of materials is chosen, and a final stage, during which the material quality as well as the heat treatments it has been subjected to are mentioned in order to satisfy the functional necessities.

2.1. The preselection stage

- Starting from the design data, based on the ratio:

$$M_t = 9{,}55 \cdot 10^6 \frac{N}{n} \quad [\mathrm{N \cdot mm}] \tag{1}$$

the moment of rotation that strains the gear is calculated, and multiplying by the respective transmission reports, the moments that strain the other gears within the mechanism are calculated.
Tabel 1 [3] allows us to observe, at a first approximation, the function modulus of the moment of rotation.

Table 1. The modulus dependent on the moment of rotation

M_t [N·m]	m [mm]	M_t [N·m]	m [mm]
< 10	max 1,25	120…200	4,00…5,00
10…20	1,25…2,00	200…300	5,00…6,00
20…35	2,00…2,25	300…500	6,00…8,00
35…60	2,25…2,50	500…750	8,00…10,00
60…120	3,00…4,00	750…1000	10,00…12,00

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- Considering a number of preliminary teeth z_{1p} for the pinion, a certain dividing diameter results from the relation (2):

$$d_1 = mz_{1p} \text{ [mm]} \quad (2)$$

- Based on the relation (2) in the Tabel 2, a series of peripheral speeds have been calculated for a range of possible rotative speeds and dividing diameters. As it can be noticed, the tabel has been divided into three sections, according to speed.

$$v_1 = \frac{\pi d_1 n_1}{60000} \text{ [m/s]} \quad (3)$$

The calculated speed for the concrete case fits within one of these sections, and according to this we can establish the group of materials [1].

Section I, with speeds below 1,0 m/s comprises the category of slow and very slow gears. Their resistance to wear can be satisfied by cast iron or carburizing steel.

Table 2. Peripheral speed

n_1	d_1 [m]													
[rot/min]	**0.02**	**0.025**	**0.03**	**0.04**	**0.05**	**0.06**	**0.08**	**0.10**	**0.12**	**0.16**	**0.20**	**0.24**	**0.32**	**0.40**
3000	3.15	3.94	4.72	6.30	7.86	9.45	12.3	15.7	18.9	25.2	31.5	37.7	50.4	63.0
2400	2.52	3.14	3.76	5.02	6.58	7.55	10.1	12.6	15.1	20.2	25.2	30.1	40.2	50.2
1870	1.96	2.45	2.94	3.92	4.90	5.90	7.75	9.80	11.8	15.7	19.6	23.5	31.4	39.2
1500	1.57	1.96	2.36	3.15	3.93	4.72	6.30	7.85	9.45	12.6	15.7	18.9	25.2	31.5
1200	1.26	1.57	1.89	2.52	3.14	3.77	5.04	6.25	7.50	10.1	12.6	15.1	20.2	25.2
950	1.00	1.24	1.49	1.99	2.49	2.98	3.98	4.97	6.00	7.95	10.0	11.9	15.9	19.9
935	0.97	1.22	1.46	1.95	2.44	2.92	3.90	4.88	5.87	7.80	9.70	11.8	15.7	19.6
800	0.84	1.05	1.26	1.67	2.10	2.51	3.36	4.20	5.02	6.70	8.35	10.2	13.4	16.8
750	0.78	0.98	1.18	1.57	1.96	2.36	3.15	3.93	4.70	6.34	7.84	9.40	12.6	15.7
610	0.64	0.80	0.96	1.28	1.60	1.92	2.57	3.21	3.85	5.12	6.40	7.70	10.3	12.9
600	0.63	0.78	0.94	1.26	1.57	1.89	2.52	3.15	3.80	5.06	6.30	7.55	10.1	12.6
475	0.50	0.62	0.75	1.00	1.24	1.50	2.00	2.08	3.00	4.00	5.00	6.00	8.00	10.0
400	0.42	0.52	0.63	0.84	1.04	1.26	1.67	2.00	2.52	3.35	4.20	5.05	6.70	8.40
375	0.39	0.49	0.59	0.78	0.97	1.18	1.57	1.96	2.35	3.14	3.92	4.70	6.28	7.84
320	0.33	0.42	0.51	0.67	0.84	1.00	1.34	1.68	2.02	2.68	3.35	4.02	5.36	6.70
300	0.31	0.39	0.47	0.63	0.78	0.94	1.26	1.57	1.89	2.52	3.15	3.78	5.02	6.38
240	0.25	0.31	0.38	0.50	0.63	0.76	1.00	1.26	1.55	2.02	2.52	3.02	4.03	5.05
200	0.21	0.26	0.31	0.42	0.52	0.63	0.84	1.85	1.26	1.68	2.10	2.52	3.36	4.20
150	0.16	0.20	0.29	0.32	0.39	0.47	0.63	0.78	0.94	1.26	1.57	1.89	2.52	3.15
125	0.13	0.16	0.20	0.24	0.33	0.39	0.52	0.66	0.78	1.05	1.30	1.57	2.10	2.62
100	0.12	0.13	0.16	0.21	0.26	0.32	0.42	0.52	0.63	0.83	1.04	1.26	1.68	2.10
80	0.08	0.10	0.13	0.17	0.21	0.25	0.34	0.42	0.50	0.67	0.84	1.00	1.34	1.67
60	0.06	0.08	0.09	0.13	0.16	0.19	0.25	0.32	0.38	0.50	0.63	0.76	1.01	1.26
40	0.04	0.05	0.06	0.08	0.11	0.13	0.17	0.21	0.25	0.34	0.42	0.51	0.67	0.84
20	0.02	0.03	0.03	0.04	0.05	0.06	0.08	0.11	0.13	0.17	0.21	0.25	0.37	0.42
10	0.01	0.01	0.02	0.02	0.03	0.03	0.04	0.05	0.06	0.08	0.10	0.13	0.17	0.21
Obs.			Section I				Section II				Section III			

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Section II, with speeds below 4 m/s, comprises the groups of improved quality plain or alloyed carbon steels, hardened and tempered to various temperatures. Following heat treatments of hardening and tampering, they get perlite, troostite or bainite structures. The lower the tampering temperature, the higher the steel temper, but the lower its tenacity [4]. In those cases in which the dynamic effects are lower and the peripheral speed is higher, improvement plain carbon steels are preferred, and when the gear functions in harsh conditions, at low speeds, accompanied by strong dynamic effects, alloyed steels for hardening and tempering are preferred.
Section III comprises relatively high peripheral speeds, where the danger of wear is imminent. As hard materials are needed, carbon or alloyed carburizing steels are preferred.
The group, of improvement superficially hardened steels, is chosen only in the case of lighter load regimes, because the whole section is hardened and the tooth becomes brittle. The method is only efficient for big modulus gears.
The group of carburizing steels is the one most often used. It covers the necessities of any rotative speed, any power and any working environment. In the case of extremely high strains, the alloyed carburizing steels are used, as a double hardening (hardening I for the core and hardening II for the thermally treated layer) followed by tempering is applied to these ones as a result of carburizing.
The ionic or gas nitralloyed steels will be used only in light or medium strains, in the context of high rotative speeds. Heavy strains may jeopardize the integrity of the piece by marking the nitride layer, which is thin and lain on a soft base.

2.2 Choosing the pinion material

It is done by calculating the effective tension at contact and tooth base bending pressure, on fatigue conditions [3].
Strain at contact pressure may be written as (4) or (5):

$$\sigma_H = Z_E Z_H \sqrt{\frac{2M_t}{bd_1^2} K_A K_V K_{H\beta} \frac{u \pm 1}{u}} \tag{4}$$

$$\sigma_H = Z_E Z_H \sqrt{\frac{2M_t}{\Psi_m m^3 z_1^2} K_A K_V K_{H\beta} \frac{u \pm 1}{u}} \tag{5}$$

$$\sigma_H = Z_E Z_H \sqrt{\frac{2K_A K_V K_{H\beta}}{\Psi_m z_1^2}} \sqrt{\frac{u \pm 1}{u}} \sqrt{\frac{M_t}{m^3}} \tag{6}$$

The following calculus factors are chosen:
$Z_E = 272$ - for steel;
$Z_H = 1,84$ - for $\alpha = 20^0$;
$K_H = 1,25$ - for reducers that are powered by electric motors;
$K_V = K_{H\beta} = 1,2$ - for predimensioning;
$\Psi_m = \Psi_d z_1 = \frac{u+1}{2} \Psi_a z_1$;
$z_1 \approx 20$.

The factors and coefficients are replaced and the ratios tension-contact pressure are obtained, according to the value of the ratio gearing, moment of rotation and dividing diameter or modulus and number of teeth. These relations are presented in Tabel 3.
For tooth base bending strain, on conditions of fatigue, the maximum tension can be written with this formula:

$$\sigma_F = \frac{2M_{t1}}{bmd_1} K_A K_V K_{F\beta} K_{F\alpha} Y_{Fa} \tag{7}$$

or

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$$\sigma_F = \frac{2K_A K_V K_{F\beta} K_{F\alpha} Y_{Fa}}{\Psi_m z_1} \cdot \frac{M_{t1}}{m^3} \quad (8)$$

which becomes (9) for the above established values of coefficients and factors and for $K_{F\beta}$ = 0,6, Y_{Fa} = 2,2.

$$\sigma_F = 1{,}59 \cdot 10^{-2} \frac{M_{t1}}{m^3} \quad (9)$$

Table 3. The relations tension contact pressure dependent on the transmission ratio [5]

u	σ_H [MPa]	Relation nr.
1,00	$21{,}23\sqrt{\frac{M}{m^3}}$	*(10)*
1,25	$18{,}98\sqrt{\frac{M}{m^3}}$	*(11)*
1,60	$16{,}78\sqrt{\frac{M}{m^3}}$	*(12)*
2,00	$15{,}01\sqrt{\frac{M}{m^3}}$	*(13)*
2,50	$13{,}42\sqrt{\frac{M}{m^3}}$	*(14)*
3,15	$11{,}96\sqrt{\frac{M}{m^3}}$	*(15)*
4,00	$10{,}61\sqrt{\frac{M}{m^3}}$	*(16)*
6,30	$8{,}45\sqrt{\frac{M}{m^3}}$	*(17)*
8,00	$7{,}5\sqrt{\frac{M}{m^3}}$	*(18)*

3. PRINCIPLES IN CHOOSING THE MATERIAL AND THE TREATMENT OF THE DRIVEN WHEEL

The machine design must be made in such a way that the functioning period ensures the foreseen reliability, and the wear speed is approximately the same for the entire kinematic chain.

The functioning conditions differ from one gear to another, according to the machine position within the kinematic chain. This particularity makes the choice of materials and heating treatments for each pinion unique. If the choice of pinion material is defined by functional parameters, as shown in the previous chapter, the choice of gear wheel material is determined by the pinion material and heat treatments, as well as by the tribological conditions. By considering pinion material and heat treatments, the driven wheel is protected against grabbing, electroerosion and plastic strains and its resistance to fatigue is ensured. The lubricant, the third insert in between the flanks surfaces, protects them against direct contact, participates in the transmission of movement by the HD or EHD uninterrupted film, hinders pitting or

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exfoliation [1]. The choice of driven wheel material and treatment may be made according to the hard-hard; hard-semihard, hard-soft, soft-soft couples.

Group I (increased hardness of pinion and wheel)

It is characteristic for gears whose gear wheels are made of carburizing materials, thermochemically treated and superficially hardened by tempering to carburized or carbonitrided materials or even ironical or gas nitrided ones. This is the category of materials that is most often used in making gear wheels.

In these cases, the superficial hardness of the pinion teeth flanks varies from 56 to 65 HRC. The hardness of the driven wheel, usually made of the same material and suffering the same thermochemical treatment as the pinion itself, must be 2-4 HRC lower in order to avoid grabbing during the semifluid lubrication periods at the start and at the end.

The category of case-hardened or carbonitrided materials – the thermochemically treated layer has a thickness of δ=0,6…1,2 mm, which is enough to support a finishing operation, by rectification, following the thermochemical treatment. During finishing approximately 0,2 mm are removed from the thermochemically treated layer, but it remains thick enough to support exploitation strains and to avoid marking.

The category of ionic and gas nitirided materials - the thermochemically treated layer is usually thin, below 0,4 mm. Thus the teeth flanks must undergo finishing operations before the thermochemical treatment. These materials will only be used for lightly or medium strained gear wheels, to avoid the danger of marking. The high superficial hardness of these gear wheels seriously requires a high degree of flank finishing as well as ensuring the conditions of fluid lubrication. The surface microrelief of these gear wheels acts like a file on the surface of the interlinked flank during the periods of semifluid lubrication. The finishing of flanks that had previously been finished by shaving or rectification continues to take place by running in.

Group II (increased hardness in the pinion and medium hardness in the gear wheel)

It takes into consideration the same wear speed for the pinion and the gear wheel. The AGMA 218-01-A2 [7] regulations recommend:

$$\frac{H_{pinion}}{H_{roata}} = 1{,}2...1{,}7 \qquad (19)$$

Tabel 4, presents the possible range of hardness for the pinion and the necessary corresponding values for the driven gear wheel, according to the range of gear reduction rates (STAS 6012-82). Knowing the driven gear wheel hardness, the chemical treatment may be used in the case when the same material as in the pinion is used; another possibility is to choose the material and the treatments that lead to this hardness, in the case when different materials are used.

This group poses finishing problems in the pinion teeth flanks as the microrelief cuts in the interlinked flanks. The latter do not need too much finishing because it is obtained by copying the pinion microrelief after correctly performing the running in. the lack of finishing operations in the pinion teeth flanks increases wear speed and leads to laying the gear off works.

Group III (increase hardness in the pinion and low hardness in the gear wheel)

It is used for gears where the movement, i.e. the gliding, reaches high values. Specific for this category is the gear worm-spiral wheel. The worm is made of hardened steel and the spiral wheel from bronze or cast iron. The condition for them to couple is the formation of an antifriction couple.

The pinion may be made of carburizing steel superficially hardened as a result of thermochemical treatment or of carburizing steel that is casehardened and tempered at low temperatures (max. 250^0C). the driven wheel being limp, it totally copies the pinion negative geometry.

Group IV (low hardness on both wheels)

In this category we may consider gear wheels made of materials whose hardness is below 350 HB. The prescriptions in Tabel 4 are recommended here as well. The low hardness allows the pinion teeth flanks and the driven wheel flanks to be machined through milling or slotting. For this type of gears, the completion of flank finishing is done by correctly executed running in. During running in there are disturbances of the microrelief surface tips and plastic cold workings that may finish the surface, but may also close certain microcracks. Not respecting running in conditions may lead to huge disturbances, which may damage surfaces and may accelerate laying off works.

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Table 4. Hardness depending on the transmission ratio

Pinion hardness		Driven whell hardness																	
		u=1		u=1.5		u=1.6		u=2.0		u=2.5		u=3.15		u=4.0		u=6.3		u=9.0	
HB	**HRC**	HB	HRC	HB	HRC	HB	HRC	HB	HRC	HB	HRC	HB	HRC	HB	HRC	HB	HRC	HB	HRC
200	**-**	165	-	155	-	155	-	50	-	150	-	145	-	140	-	130	-	120	-
220	**-**	165	-	175	-	170	-	165	-	160	-	160	-	150	-	140	-	130	-
250	**23.0**	208	-	195	-	190	-	185	-	180	-	170	-	160	-	150	-	150	-
275	**26.9**	228	-	215	-	210	-	210	-	200	-	195	-	190	-	170	-	160	-
300	**30.3**	250	-	235	-	230	-	225	-	220	-	215	-	205	-	190	-	180	-
325	**33.0**	270	-	265	-	250	-	245	-	240	-	230	-	225	-	200	-	190	-
350	**36.0**	290	-	275	-	270	-	260	-	255	-	250	-	240	-	220	-	205	-
375	**38.5**	310	-	290	-	285	-	280	-	275	-	265	-	260	-	225	-	220	-
400	**40.7**	335	-	315	-	305	-	290	-	295	-	285	-	275	-	235	-	235	-
425	**12.8**	355	-	330	-	320	-	310	-	300	-	305	-	290	-	250	-	250	-
450	**44.8**	375	-	350	-	345	-	340	-	330	-	320	-	310	-	265	-	265	-
475	**46.7**	401	-	375	-	365	-	360	-	350	-	340	-	330	-	280	-	280	-
500	**48.3**	415	-	390	-	375	-	365	-	360	-	345	-	340	-	300	-	290	-
525	**50.0**	440	41.6	415	39.6	405	38.5	395	37.8	380	36.8	375	35.7	360	34.5	315	31.3	310	29.4
550	**51.6**	460	43.0	435	40.6	420	39.6	410	39.0	405	38.0	390	37.0	380	35.6	330	32.2	335	30.3
575	**53.0**	480	44.2	450	41.8	440	40.8	435	40.0	420	39.2	395	38.0	390	36.5	345	33.2	340	31.2
600	**54.4**	500	45.4	475	43.0	460	42.0	450	41.2	440	40.6	430	39.0	415	37.7	375	34.1	350	32.0
625	**55.8**	520	46.3	495	43.8	480	42.8	470	41.6	460	41.2	450	40.1	430	38.3	395	34.8	370	32.7
650	**37.0**	540	47.5	510	45.0	500	43.6	485	43.0	470	42.0	465	41.0	445	39.2	410	39.3	380	33.6
-	**58.0**	-	48.4	-	45.6	-	44.5	-	43.6	-	42.6	-	41.5	-	40.0	-	36.5	-	34.0
-	**59.0**	-	49.0	-	46.0	-	45.3	-	44.0	-	43.5	-	42.1	-	40.7	-	37.0	-	35.0
-	**60.0**	-	49.2	-	46.2	-	45.6	-	44.5	-	-	-	43.0	-	41.5	-	37.6	-	35.4

4. CONCLUSIONS

Because the material of the gear wheel has a decisive role in determining: the dimensions, the shape, the execution technology, the functioning period, etc., the importance of its material and heat treatment is obvious. The creation of this algorithm for choosing the material contributes to the decrease in design time and to the process optimisation.

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