CRITERIA FOR DESIGN AND TECHNOLOGY OF THE GEAR SPINDLES[1]

Enrico Ceschini[2]

Abstract

The basic components of the gear spindles are the working gear teeth, whose manufacturing implies different technologies. The widespread need of extreme rolling mill process conditions has got MAINA Organi di Trasmissione S.p.A. to successfully test, during the last seven years, a new technology called H11, which enables to remarkably increase load capacities and max speed of the spindle heads, as well as to obtain the geometry optimization of the gear teeth. Beyond a suitable, effective and easy lubrication, the H11 technology considerably reduces the factors damaging the gear teeth, like abrasive wear, heating and pitting.

Key words: Gear spindle; Gear teeth; H11.

1 *Paper presented at 42th Rolling Processes, Rolled and Coated Products Seminar of ABM; Santos, SP, October 25 to 26, 2005.*

2 *Chief Engineer, MAINA Organi di Trasmissione S.p.A., Corso Alessandria, 160 – 14100 Asti (Italy)*

A new generation of gear spindles, able to compensate working angles up to 2.5-3°, is gradually spreading in the mill stand roll drives, both in hot and cold mills, either unidirectional or reversible. These last generation spindles, having limited overall dimensions and even more limited mill roll diameters, offer:

- Very high load capacity both at the tooth flank and root
- Insensitivity to overloads
- Insensitivity to high temperatures
- Capacity of reaching high angular speeds
- Perfect seals for double direction of rotation
- Long-life special lubrications, either by grease or continuous by oil
- High torsional stiffness
- Limited tangential and radial backlash
- Non-in-line antivibration assemblies
- Dynamically balanced masses with minimum residual unbalancing

They adapt with minimum resistance to shifting drives, working roll crossing and bending, as well as to fully computer-based frequent and fast roll changes. The choice of adequate design and production solutions therefore enables reaching long operation time with a limited, easy and quick scheduled maintenance.

Besides, they are components strategic to the correct operation of the mill plants, as they transmit torques and speed to the working rolls, and must therefore be engineered so to be fully reliable in each of their aspect.

Any contact and transmission component, to be passed through a force flux, has shape, dimensions, finishing, material and heat treatment such as to make them free from fatigue failure, while conferring them a very high resistance to compression, abrasive wear, pitting and corrosion.

To make the spindle heads and their working gear teeth kinematically efficient, the thrust button and the thrust plate surfaces are aligned with the gear tooth oscillation axis. Any splined gear tooth (both static and shifting), is standardized according to DIN 5480 standards, widely dimensioned and gas nitrided, so to resist against corrosion.

Special care is devoted to the finishing and to the hardness of the roll end sleeve bore inner surfaces, mating with the roll necks, by employing heat treatments which assure a hardness higher than 56 HRC. Besides, the choice of special precautions prevents the component deformation from breaking the connecting units, under load.

Dimensioning and assembly are made in such a way as to obtain vibration levels (bending and torsional) suitable to the surface quality of the strip to be produced; this is why the gear spindle is dynamically balanced in class VDI 2060 G 6.3 at 20% more than the maximum operation speed. When required, it is possible making a non-aligned assembly of the pinion and roll end working gear teeth, so to remove any resonance phenomenon.

In these modern gear spindles, the number of the components composing the spindle is limited to the essential ones, as every engineering condition is searched, useful to limit maintenance and to make it quick, easy and inexpensive. Often, a careful standardization of the spindles in the different stands makes the interchangeability of the components possible, so reducing the spare inventory.

Lubrication is easy, quick, safe and inexpensive. The gear spindles are equipped with simple or double dynamic floating seals, with preloaded seals, assembled in such a way as to be insensitive to wear. Therefore, both in operation and during the roll change or the shifting, the lubricant dispersion in the surrounding environment is avoided, so limiting any further cleaning cost. Besides, the choice of preloaded static seals, absorbing unavoidable torsional deformations on flanges and hubs, avoid any dangerous water, steam and polluting substance entry in the spindle, as well as the problem of spline corrosion. The lubrication system, with its several charge and discharge plugs, is engineered to enable even the thrust buttons being easily and effectively lubrified. By employing sealing systems with special double seals, oil or chemical honey lubrication is carried out (Figure 1).

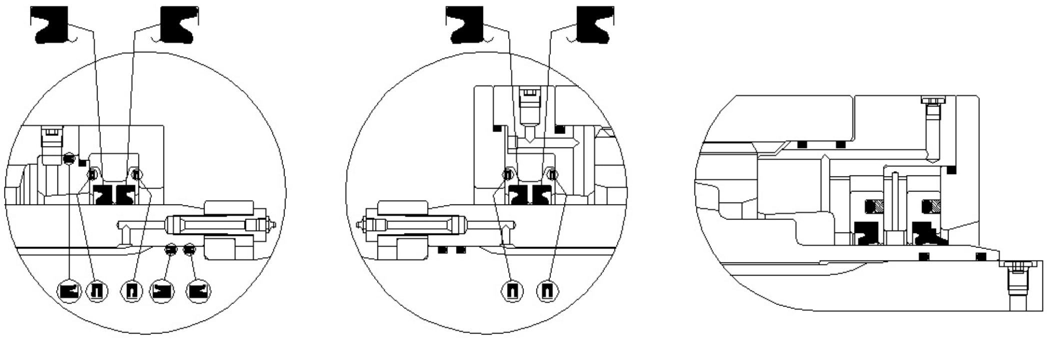

Figure 1. Sealing systems.

In case of grease lubricated spindles, you can obtain an effective lubrication by employing special long-life grease, resistant to oxidation and centrifugation, having a low consistence (NLGI 0 e 1) and a high flash point (170-250°C). They're lithium soap or complex lithium soap greases, made of very high-viscosity mineral or synthetic oils (1500-1800 cSt at 40°C) and having a high viscosity index (>100), and containing a high percentage of both chemical (EP) and solid additives (10% of MoS_2). The last ones are essential to the emergency lubrication of transient states.

As a matter of fact, the modern gear spindles can reach a Hertzian contact pressure > 2000 MPa (even > 4000 MPa during the transient states of sheet entry), a slipping speed > 0.5 m/sec, a rotation speed of 500-1000 rpm (stands F6-F7 in case of hot strip mill or F4-F5 for cold mill), temperatures of 120°C and dynamic factors PV > 20 Kw/cm^2. Under these operating conditions, the lubricant must always be high viscosity type, as it is important to keep the contact metal surfaces constantly apart, and consequently to keep the friction coefficient low (about 0.05), so limiting heating and assuring a high efficiency (power loss of 0,3-1,5 ‰ each mesh). The lubricant must be long-life type to enable, according to the operating temperatures, long interval lubrications (excellent would be two, or three-week interval lubrications).

On the contrary, when the installed power is about 12000 Kw each stand, as nowadays often happens in the modern plants, the dynamic factor PV and/or the slipping speed are high or the working cycle is extreme, the gear teeth need being cooled by predisposing safe and experimented forced centralized lubrication and cooling systems. In these cases, the power level passing through a spindle is such to make its two outer surfaces (sleeve and shaft portion) unable to naturally disperse by conduction, radiation and convention (total exchange coefficient of 35-45 $KCal/h/m^2/°C$) the heating store caused by the power loss by efficiency of the gear teeth of each spindle head.

These lubrication systems require a recirculation of lubricant oil type EP (ISO VG 680) suitably filtered (40 micron) and in pressure (1.2-2 bar). By continuously bringing fresh and cool oil (around 40-45 °C) to the gear teeth, their cooling is assured and a more effective and safe lubrication is granted. Excellent efficiency and low wear are consequently achieved. In addition, you get the advantage of eliminating periodical manual lubrication, so avoiding any risk of forgetfulness and carelessness. Finally, the forced lubrication systems are ecologically adequate, as they drastically reduce the lubricant consumption and the consequent environmental pollution (Figure 2).

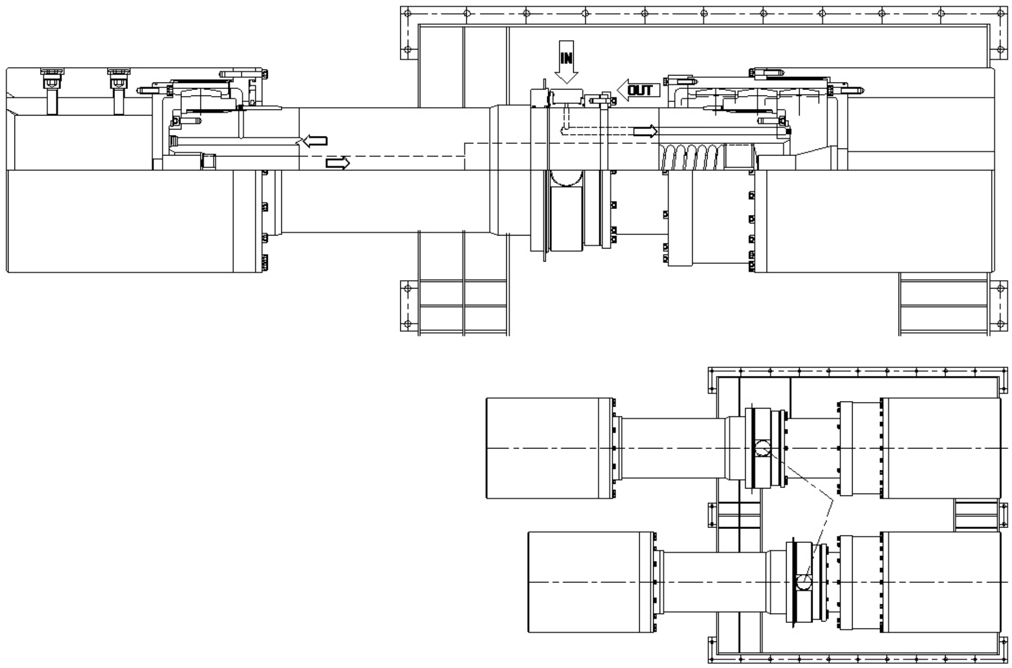

Figure 2. Spindle design for continuous oil lubrication.

The basic components of the gear spindle are the working gear teeth.
For their manufacturing, we employ special alloy steels submitted to several heat treatments, depending on the load and operating features to be assured:

42CrMo4 IHT
Hardened and tempered 42CrMo4 steel, with induction tempering treatment
42CrMo4 NGN
Hardened and tempered 42CrMo4 steel, with gas nitriding treatment, so to reach a standard hardening depth (0.55 mm) and a surface hardness higher than 600 HV.
31CrMo12 SGN
Hardened and tempered 31CrMo12 steel, with gas nitriding treatment, so to reach special hardening depths (0.65 mm) and a surface hardness higher than 750 HV.
18NiCrMo5 CHG
18NiCrMo5 steel with case hardening, tempering and drawing, so to reach a surface hardness >58 HRC, a core hardness >40 HRC, a case hardening depth equal to 0.2*module (distance where 550 HV are to be measured) and total depth of carbon spreading equal to 1,5*of useful depth, with a steel having an elongation of 10-12% and a resilience >28 J. The tooth profile is fully ground and any dimensional and geometric error is contained within Agma 12 precision class.
With this technology, it is essential grinding the gear tooth profile, the center and reference diameters after the final heat treatment, both to remove any unavoidable deformation and

to confer the gear teeth a proper geometric and dimensional precision. This grants a more uniform load distribution on the gear tooth flanks (involute precision) and a bigger number of meshed gear teeth (pitch precision).
However, the CHG technology is no more sufficient to meet any application requirement. While searching new technologies, aimed at improving the load capacity and the gear tooth lifetime, MAINA Organi di Trasmissione S.p.A. has carried out studies to find gear teeth having high root resistance (bending strength), and whose flanks are able to resist against abrasive wear and against high Hertzian pressure (contact stress), while searching the max surface hardness, the max useful hardening depth and the max core toughness as regards the basic material. As a result of this search, we're now employing a new technology called H11:

X38CrMoV51 SGNG
X38CrMoV51 steel, submitted to special and complex sequences of core heat treatments and surface thermochemical treatments, together with more and more accurate and higher precision class and surface finishing, both on the flank and on the head of the tooth (shape grinding).
This technology has been employed during the last seven years so many times and so successfully that the positive results reached in some extreme applications lead us thinking that in the next future this type of steel will be more and more employed in working gears, to solve problems of life and / or load, working angles and high rotation speed (Figure 3).

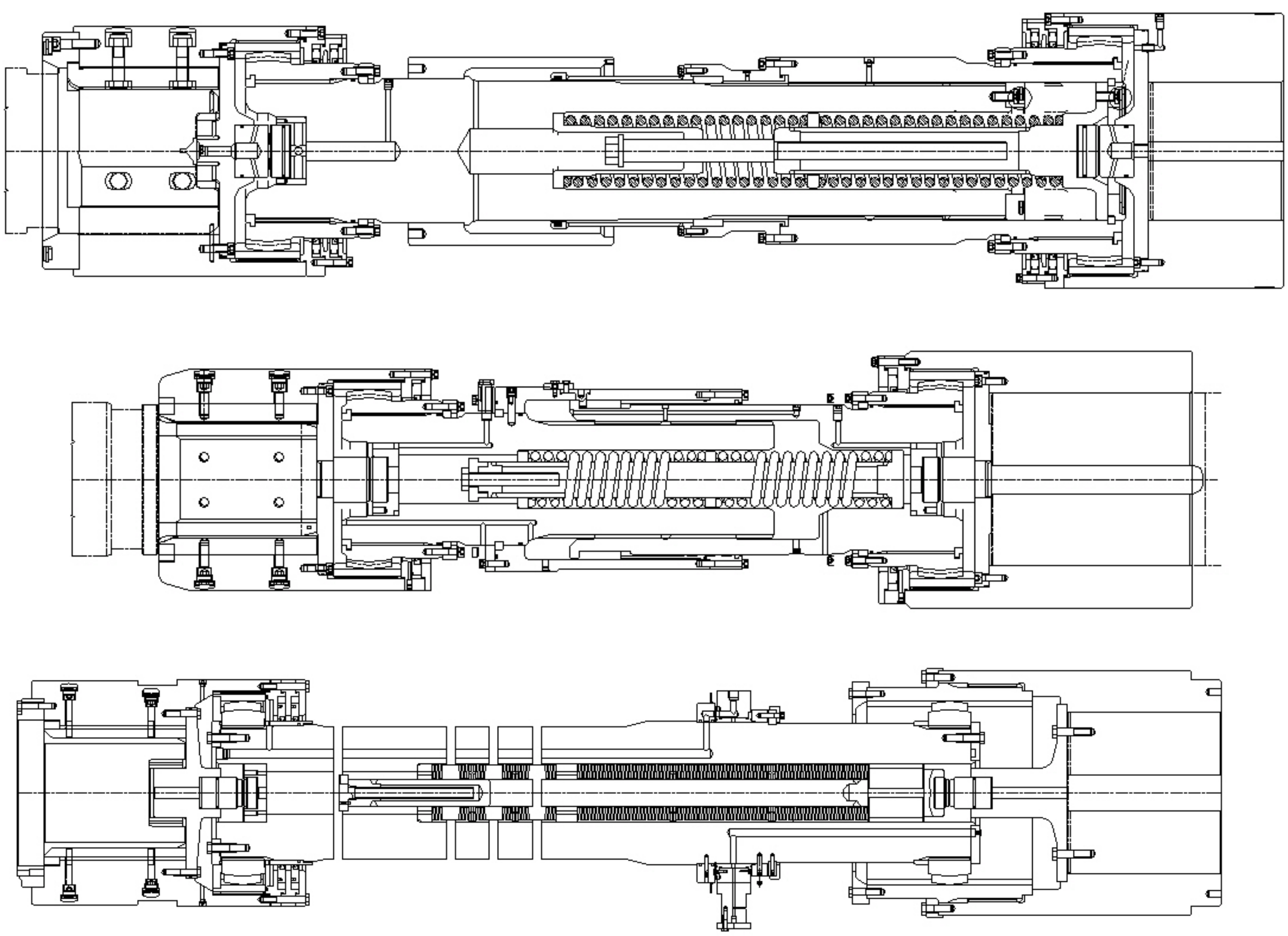

Figure 3. Examples of gear spindles in X38CrMoV51 SGNG

Gear teeth with core hardness of 50-52 HRC and surface hardness of 1000-1100 HV1, useful depth of 0.4 mm (where 700 HV1 are to be measured), total diffusion depth of 0.75 mm with a steel having an elongation equal to 14-18% and a resilience higher than 24 J.
To further increase the fatigue limit, the working gear teeth are submitted to final shot peening treatment.
The intermediate shafts and the sleeves housing the wear adapters are always made of 40NiCrMo7 steel, hardened and tempered at 270-300 HB, and the splined ends are always gas nitrided to increase the tooth flank surface hardness.
Usually, the roll end sleeves are equipped with outer and inner center rings mating with wear flat keys, or the center rings are replaced by round keys. If the roll end bore has small dimensions (<480 mm), the whole sleeve can be nitrided, but for larger diameter bores it is advisable employing flat keys or integral bores with surfaces induction tempered at medium, low frequency, so to reach useful depths of 3.5-4.5 mm and surface hardness >56 HRc. In this case, a final drawing at 180-200 °C is necessary.
Each of these technologies has defined load limits, according to the dimensions, as well as a max employ heat limit: 120 °C for CHG, 150 °C for IHT, 250 °C for NGN and SGN, and 350 °C for SGNG.
For each of the above described technologies, two different grades of materials with pertaining heat treatments and checks are normally possible, so to limit costs. As a matter of fact, the more sophisticated the technology is, the more precise the material grade is and the longer the gear tooth life is, even if the costs are higher.
The diagrams below show the trend of the pulsating fatigue torque (graph, Figure 4) and of the maximum allowable speed (graph, Figure 5), depending on the size of the spindles (pitch diameter of the working gear teeth expressed in cm). It is obvious that the load capacity of H11 solution is definitely higher than in the hardened and tempered solution, as shown in the last diagram normalizing the data compared with IHT 42CrMo4 solution (graph, Figures 6 and 7).

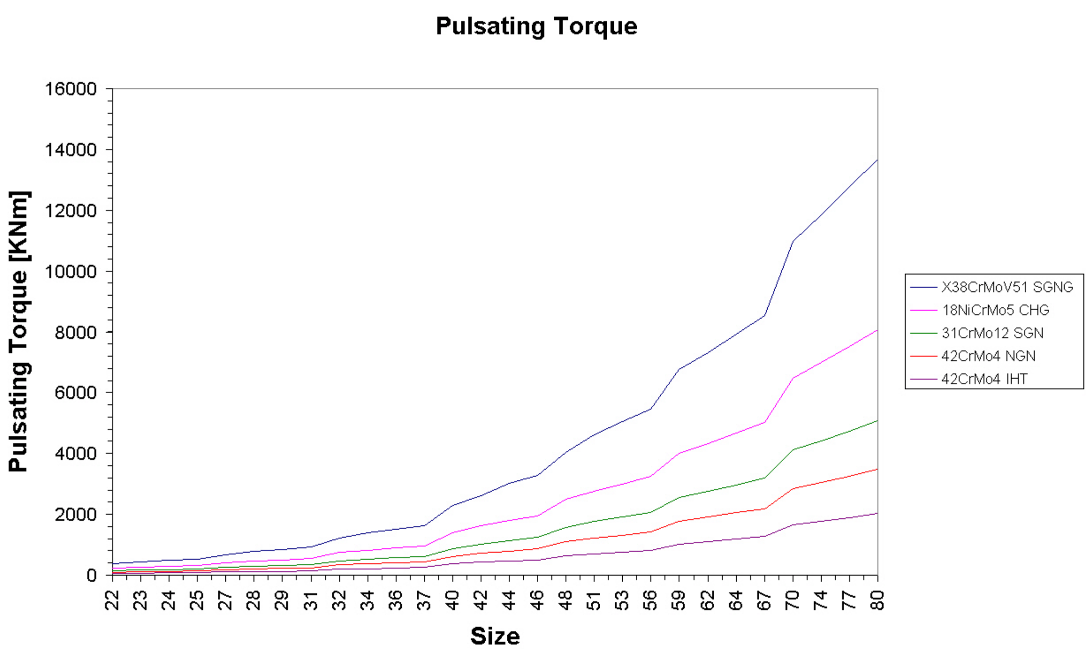

Figure 4. Pulsating fatigue torque

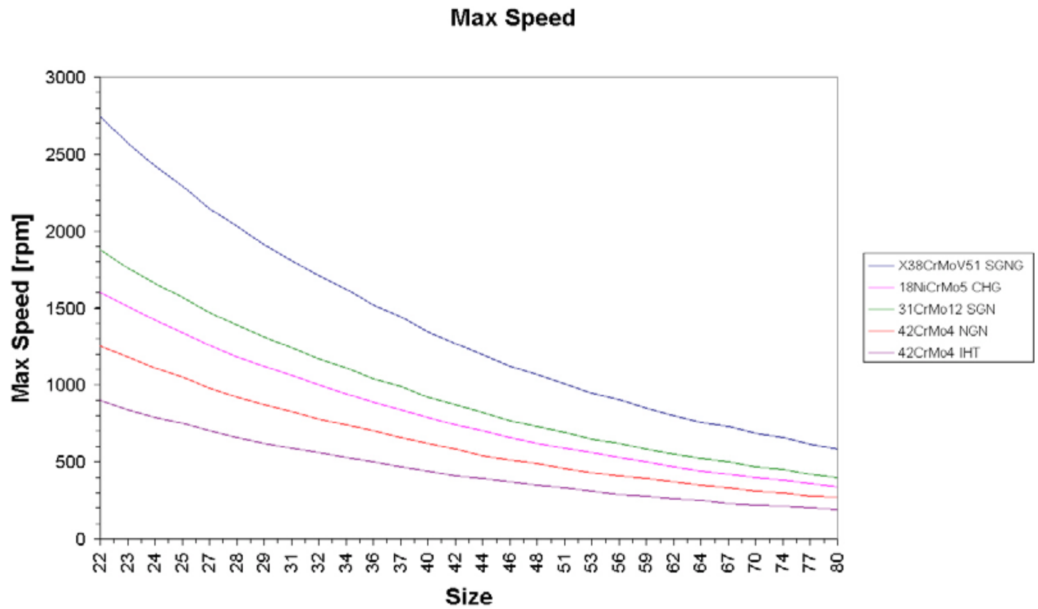

Figure 5. Max allowable speed.

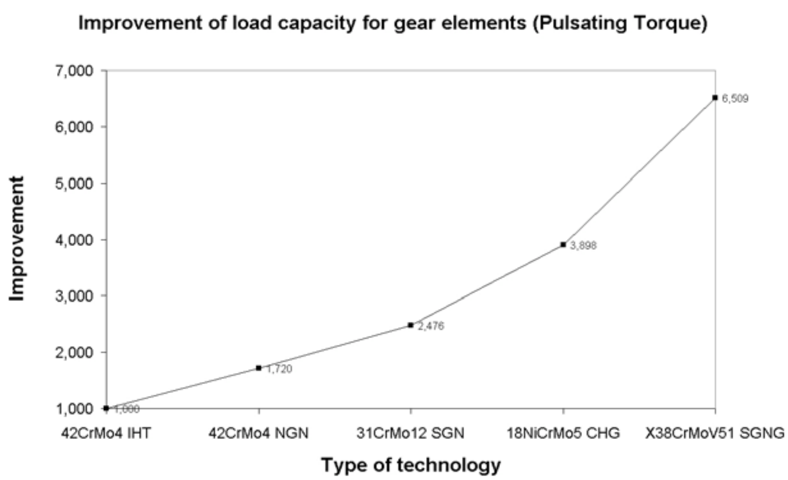

Figure 6. Improvement of load capacity for gear elements (Pulsating Torque).

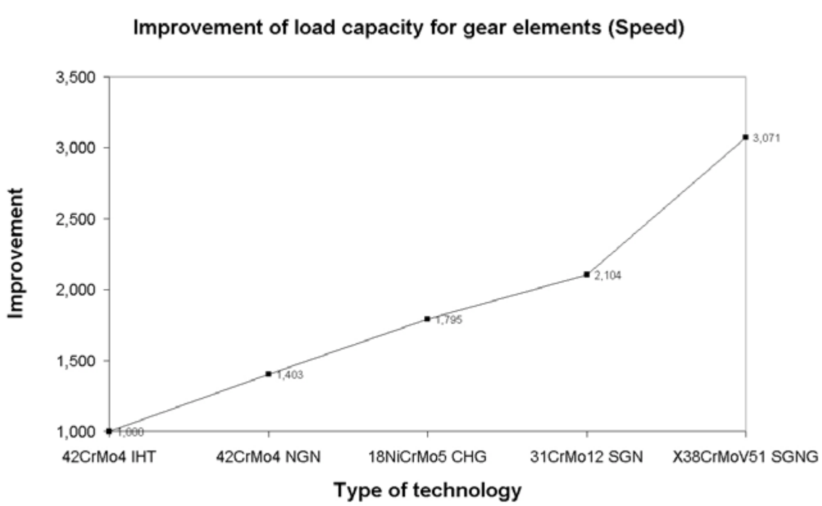

Figure 7. Improvement of load capacity for gear elements (Speed))

These technologies have been possible thanks to the progress made in the technological fields of steel and heat treatments. The uses of CHG and of SGNG, safe at present, are mainly connected with the developments made in grinding by profiled wheels as, thanks to these machineries, both the inner female gear teeth and the large crowned outer male gear teeth can be accurately ground. The previous heat treatments under press, the lapping finishing, the induction tempering after case hardening, proved to be inadequate to contain, or to remove distortions and deformations after treatment. Besides, the previous grinders for inner surfaces were not rigid enough to keep the straightness and the tooth shape on the whole length of the female gear teeth, while the grinders for outer surfaces could not grind the largest crowned male gear teeth.

In the spindle heads, the sleeve female gear teeth has straight teeth, therefore the head and the bottom diameters, along with the tooth flanks are parallel. On the contrary, the hub male gear tooth is obtained on a theoretical sphere and has therefore rayed head and bottom diameters (different size of radius) and crowned flanks. The male crowned gear teeth can freely oscillate inside the straight female tooth spaces. The tooth backlash, the crowning flank radius and the male face width are the manufacturing parameters limiting the entity of oscillation (Figure 8).

Once diameter / face width ratio, along with the pressure angle is fixed, in order to avoid any load concentration on the flanks, to contain the tangential clearance and to obtain a high foot resistance, the tooth profile needs being optimized, case by case, according to the main operating parameters, like max working angle, max no-load opening or roll change angle, max working torque and peak torque.

The profile optimization is obtained by calculations through modern computer-based programs and further verification by means of CAD 3D drawing program. By suitably acting on the tooth number and shape, and consequently on their bending stiffness, the load is distributed over a large number of teeth. Obviously, these parameters are depending on the module, the pressure angle, the profile movements, the tooth height, the tooth backlash and the flank crowning radius.

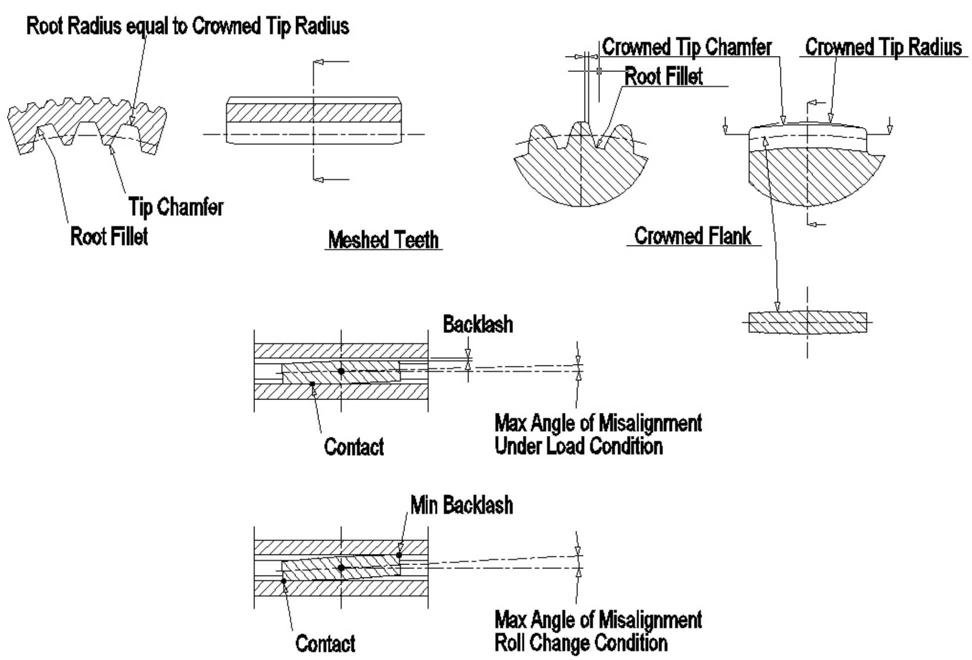

Figure 8. Gear tooth shape and design.

The gear teeth are made by special cutting tools, like hobs and special cutters, as well as CBN shaped grinding wheels. As a matter of fact, the chamfers and the head and root radius present on the male and female teeth are obtained by means of tools having a suitably modified profile (head radius and bottom semi-topping). Being the two gear teeth mutually centered (the hub head diameter is centered with the sleeve bottom diameter), the chamfers present on the male head corner avoid the interference with the female bottom corner, which is rayed. On the contrary, the tooth connection bottom radius are necessary to avoid high load concentration on the tooth root, while the female head corner chamfers are to avoid any vibration while the teeth are oscillating (Figure 9).

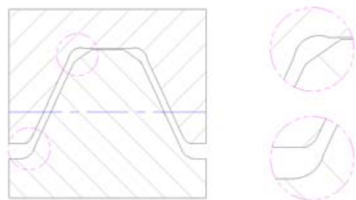

Figure 9: Toothing details.

The abrasive wear and the heating are, together with the pitting, the elements damaging the gear teeth, and are generated by the oscillating movement that the gear teeth make under load to compensate the working angle.
The factors determining heating and abrasive wear are the rotation speed, the oscillation width (working angle) and the tangential load among the teeth. To check wear and heating, all these data are summarized and evaluated in the dynamic factor PV (Hertzian pressure multiplied by slipping speed). The equation giving PV is:

$$PV = \sqrt{\frac{0.2 * E * F_t}{rb * lu}} * \frac{2 * Z * m * tg\,\beta * n}{600} \qquad \left[\frac{Kw}{cm^2}\right]$$

where:
Ft = tangential force on the tooth [KN]
E = elasticity modulus of the steel [KN/mm^2]
rb = crowning radius on the tooth flank [mm]
lu = contact useful length [mm]
m = module
Z = number of teeth
β = working angle [deg]
n = rotation speed [rpm]
With oil lubrication, PV may reach values of 16-20 Kw/cm^2 (max allowed value in case of cooling realized by forced continuous oil lubrication), while by a normal grease lubrication PV may reach values of 10-12 Kw/cm^2. Normally, with H11 technology, it is not necessary verifying the value of PV, and the thermal rating since the gear teeth can constantly work at an inner temperature of 200 °C, with peaks of 500 °C.
The pitting phenomenon on the tooth flank, on the contrary, is caused by the very high Hertzian contact surface stresses which are generated on the flanks, linked to the flank crowning (no-load angle) and to the number of teeth meshed (working angle).

The base geometric and dimensional configuration of the gear teeth (shown in the previous pictures), optimized as described above, enables obtaining an excellent gear tooth centering, minimum tangential clearance, high number of teeth meshed, a limited Hertzian contact pressure and a high resistance at the tooth root.
To be successful, an application needs to mix a suitable choice of materials and heat treatments to be employed, together with the proper type of lubrication. These last parameters are depending on the torques to be transmitted, on the max rotation speed, on the power installed, on the max working angle, on the slipping speed, as well as on the value of PV, on the natural cooling capacity, on the max operating temperature, on the production rate and on the expected lifetime.
Below some advantages resulting from a good geometric dimensioning along with an adequate selection of materials:

- An excellent geometry avoids corner failure on the tooth head and at the end of the face width
- Limited root stress and large connection radius avoid fatigue failure
- A low contact Hertzian pressure and hard surfaces limit wear and pitting, and therefore extend lifetime
- A limited tangential and radial clearance, a high torsional stiffness and an accurate dynamic balancing avoid bending and torsional vibrations
- An excellent radial centering, a low tangential clearance, tooth profile with chamfers and connection radius avoid low speed vibrations and / or torques
- Suitable materials, heat treatments and finishing avoid problems of wear and heating linked to high values of PV and slipping speed

Nowadays, the wider choice of materials and heat treatments available, the improvements in the manufacturing and checking technologies, the modern and effective computer-aided calculation systems and FEM verifications, together with the three-dimensional drawing system, have enabled achieving the highest optimization of any manufacturing parameter of a gear spindle. We're therefore able to choose, for each application, the solution representing the best technical-economical compromise or the quality top. However, to better predispose a gear spindle design, you need to know the following parameters:
- type of machine to be driven - rotation speed
- Min and max working angle - max no-load angle
- Motor power - spindle torque (min., max. and peak torque)
- TAF entity - type of drive (unidirectional or reversible)
- Number of entries / hour (cycle frequency) - working cycle times (rolling mill process - wait)
- Year production - lubrication system (standard or recirculating)
- Ambient temperature and aggressiveness - required lifetime

When studying a gear spindle project, some of the above listed parameters are evaluated according to the following scheme (Table 1):

Table 1. Selection of steel and heat treatments

Material	Load Intensity				Shock Intensity				Working Angle				No Load Angle				Operating Speed				Operating Temperature			
	L	M	H	V	L	M	H	V	L	M	H	V	L	M	H	V	L	M	H	V	L	M	H	V
SGNG				X				X				X				X				X				X
CHG			X				X				X				X			X			X			
SGN		X				X				X				X					X				X	
NGN	X				X					X				X				X				X		
IHT	X				X				X				X				X				X			

L=Light M=Medium H=Heavy V=Very Heavy

CRITÉRIOS PARA PROJETO E TECNOLOGIA DE ALONGAS ESTRIADAS

Enrico Ceschini

Resumo

Os componentes básicos das alongas estriadas são os dentes de trabalho do engrenamento, cuja fabricação envolve diferentes tecnologias. As condições extremamente severas dos processos de laminação propiciaram à MAINA ORGANI DI TRASMISSIONE SpA, através de testes bem sucedidos durante os últimos sete anos, uma nova tecnologia denominada H11, a qual permite significativos aumentos da capacidade de carga e velocidade máxima das juntas da alonga, bem como a otimização da geometria das estrias dentadas.Além de uma lubrificação adequada, efetiva e de difícil aplicação, a tecnologia H11 reduz consideravelmente os fatores que causam danos das estrias dentadas, tais como desgaste abrasivo, aquecimento e fadiga ("pitting").

Palavras-chave: Alonga estriada; Dentes de engrenagens; H11.