MATÉRIAUX ET TRAITEMENTS DE SURFACE

MATERIALS AND SURFACE TREATMENTS

TITRE / *TITLE* : ISOTHERMAL HEAT TREATED NODULAR IRON WITH AUSTENITIC-BAINITIC MICROSTRUCTURE AS MATERIAL FOR GEARS

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1
Introduction

The use of nodular iron in the engineering industry is increasing rapidly. The tensile strengths of the most general grades of nodular iron standardized in different countries range from 400 to 800 Nmm^{-2}. It is, however, feasible to improve the strength properties of these grades through heat treatment in the same manner as those of steels.

The experiences the Karkkila Foundry of Kymi Kymmene Engineering has gained from the use of nodular iron in various applications have been favourable. Especially, the experiences gained by using nodular iron in gear wheels showed that the properties of nodular iron could be further developed. In collaboration with the Santasalo Factory, which belongs to the same concern as the Karkkila Foundry, and is known as a manufacturer of gear units, an intensive development of strong nodular iron grades was started. The goal was to improve both the static and dynamic strength properties, toughness and above all, the endurance limit for surface stress, which in many cases determines the transmitted power of the gear wheels.

The research and development work resulted in the innovation of a new nodular iron grade KYMENITE-9805 for which a patent has now been granted in 5 countries (Belgium, the USA, Finland, Norway, the UK). A patent application has been filed in 13 countries. The excellent properties of this material which in several respects exceed the expextations are, in the first place, due to retained austenite. This has been produced through the isothermal heat treatment i.e. modified austempering and remains stable within a wide range of working temperatures(fig. 1)

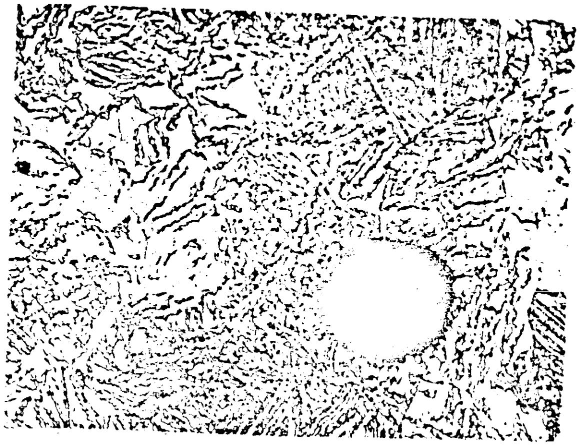


Fig. 1 The microstructure of K-9805

2
Production of the nodular iron K-9805

The austenitic-bainitic microstructure is caused by isothermal quenching after austenitising. Besides trying to obtain bainite the highest possible retained austenite content (20...50 %) is hoped for. The treatment temperature and time are, in addition to the alloying, the most important factors affecting the final result (fig. 2 and 3).

The heat treatment produces a homogenous microstructure whose properties are not dependent on the wall thickness to the same extent as they are with components in "as cast" condition. By slightly alloying with substances increasing the hardenability it is possible to manufacture components with wall thicknesses up to 100...150 mm.

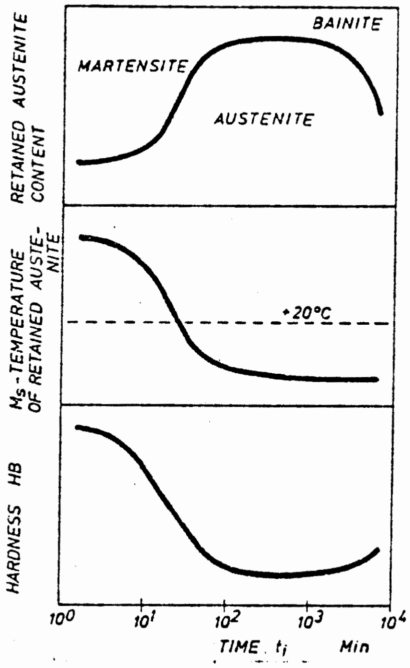


Fig. 2
The dependence of retained austenite, its M_S-temperature and hardness on the transformation time in the salt bath

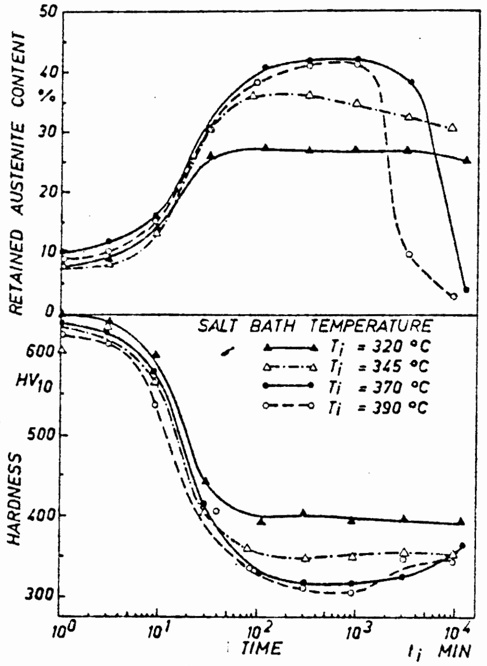


Fig. 3
The effect of transformation temperature and time on retained austenite content and hardness

3
The most important properties

3.1
Stability of the retained austenite

The stability of the retained austenite that forms in connection with the bainite mechanism is explained as follows: When austenite isothermally transforms in the salt bath, the high silicon content of K-9805 (2.0...2.8 %) effectively impedes the forming of cementite - the carbon content of the remaining austenite increases, the austenite stabilizes and the bainitic reaction slows down.

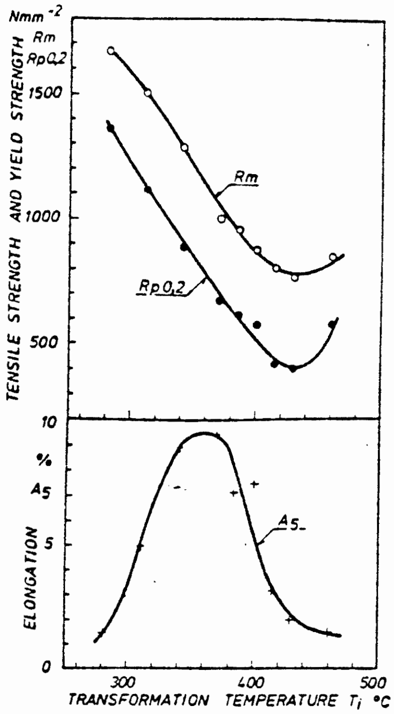


Fig. 5
The effect of transformation temperature on the yield strength, tensile strength and elongation

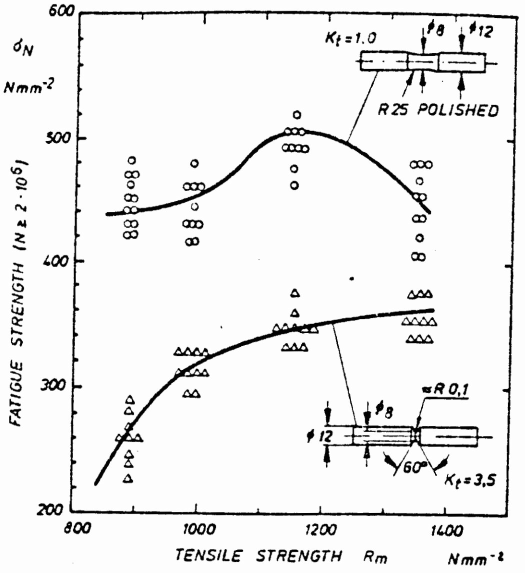


Fig. 6
The dependence of bending fatigue strength on tensile strength (transformation temperature acc. to fig. 5 and transformation time after max. retained austenite content fig. 3)

3.3
Dynamic strength properties

The best fatigue strength is attained by a microstructure whose content of stable retained austenite is greater. With the increasing strength also the internal notch sensitivity for the graphite spheroids increases and thus the meaning of the external notch decreases. The work hardening due to the machining of the notch has the same effect. When the machining is carried out after the heat treatment, a notch sensitivity of η = 0.1...0.2 is obtained (fig. 6). When the heat treatment is carried out after the machining, a notch sensitivity factor of η = 0.4 can be used. In the latter case the fatigue strength must be reduced by about 10 % when using an unnotched test bar and by about 30 % when using a notched bar (α = 3.5).

The favourable effect of the work hardening phenomenon is based on the martensite reaction on the surface of the work piece, activated through cold working. Because of the 4 % larger volume of martensite there arises a compressive stress in the surface zone which is advantageous in regard to the fatigue strength. Since work hardening is based on the phase transformation it is extremely stable. By shot peening the tooth root of the gear (fig. 7) its bending-fatigue strength improves by more than 60 % compared to a tooth hobbed after the heat treatment, and by about 100 % compared to a tooth hobbed before the heat treatment (fig. 8). Work hardening also decisively increases the loadability of machine components exposed to surface stresses because these stresses cause a martensite reaction in the surface zone. The hardness of the martensite phase is about 900 HV 0.1. This increases the hardness of the contact surface during work by about 70...200 HV (fig. 9). Since the work hardening proceeds together with the surface wear, the load-carrying ability of the surface remains unchanged during the whole service life of the component.

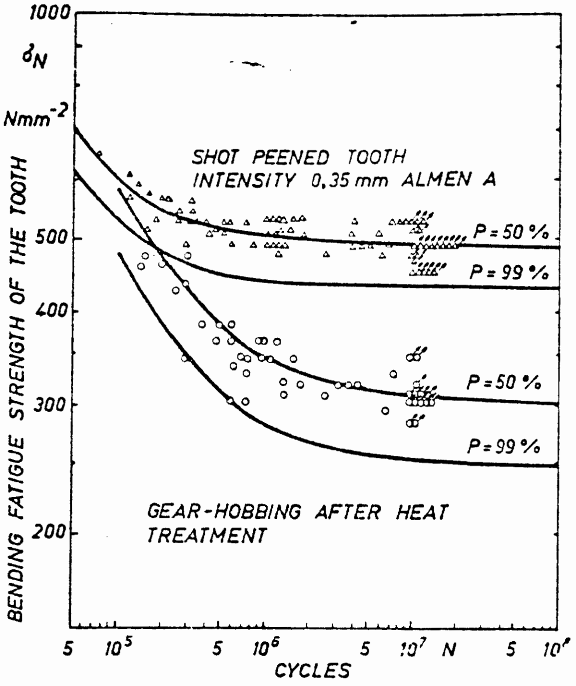


Fig. 7
The bending fatigue strength of a gear tooth improved by shot peening.
Test wheel: m = 3.5,
z = 37, b = 20, $r_{f/m}$ = 0.38
Ti = 350°C, t_i = 3.5 h

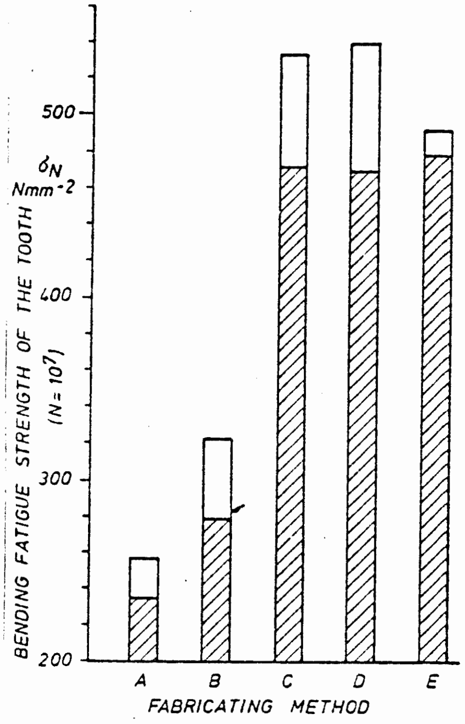


Fig. 8
A Heat treatment after hobbing
B Heat treatment before hobbing
C Shot peening 0.35 Almen A
D Shot peening 0.45 Almen A
E Shot peening 0.55 Almen A

3.4
Wear resistance

Recent studies have shown that both the abrasive (fig. 10) and adhesive wear resistance of K-9805 are about twice that of quenched and tempered steel of equal hardness. The abrasive wear resistance was tested by using test bars which rotated in a circle in quartz sand. The hardness of the test bars did not affect the wear resistance; the retained austenite seemed to be of greater importance. The adhesive wear resist-

Due to the high carbon content of the retained austenite, about 1.6 %, its M_s-temperature is very low. It has been proved experimentally that the retained austenite content does not change within the temperature range of -80°...+300°C (fig. 4).

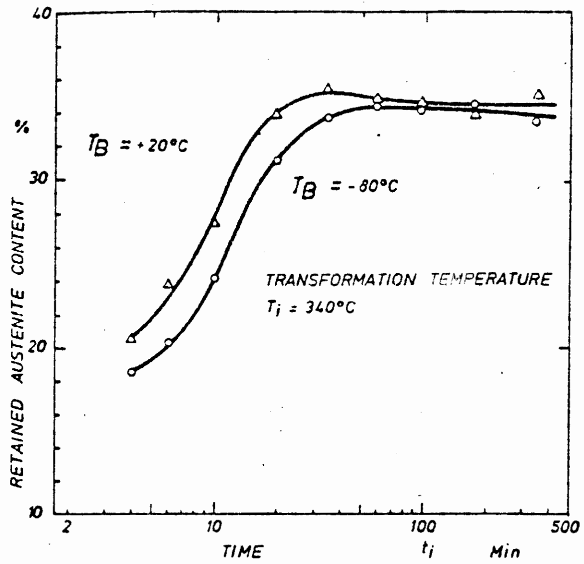


Fig. 4
The effect of working temperature T_B on retained austenite content as dependence of the transformation time t_i

In this kind of thermodynamically stable retained austenite it is, however, possible to activate an isothermal martensite reaction above the M_s-temperature by cold working the austenite. The martensite which develops through work hardening only forms in zones which have been cold worked. Elsewhere the tough austenitic-bainitic microstructure is retained.

3.2
Static strength properties

The static strength properties are strongly dependent on the isothermal transformation temperature (Ti, fig. 5). The good strength obtained at low temperatures is due to the lower bainite (fig. 2). At the higher temperatures a good toughness is obtained because of the increasing retained austenite content. When the temperature keeps rising, the austenite content starts decreasing and upper bainite or even perlite starts forming. As to the toughness, the optimal transformation temperature is 340...390°C.

ance has been tested by using both gear wheels and actual wear parts.

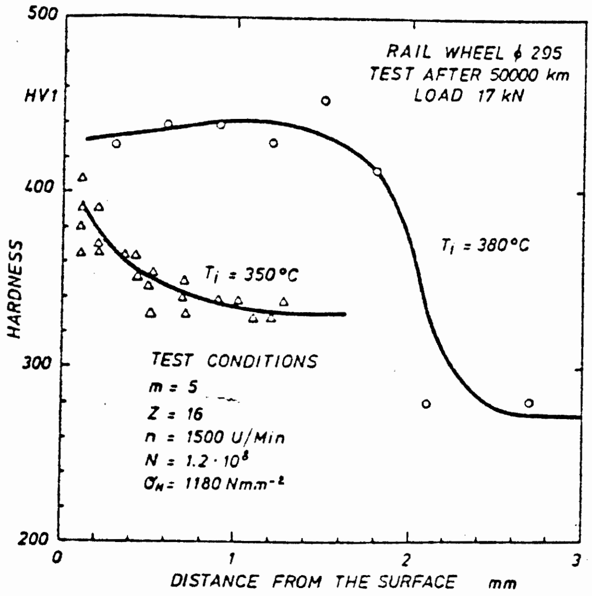


Fig. 9
The hardness increases in the surface layer of a gear wheel and rail wheel during work

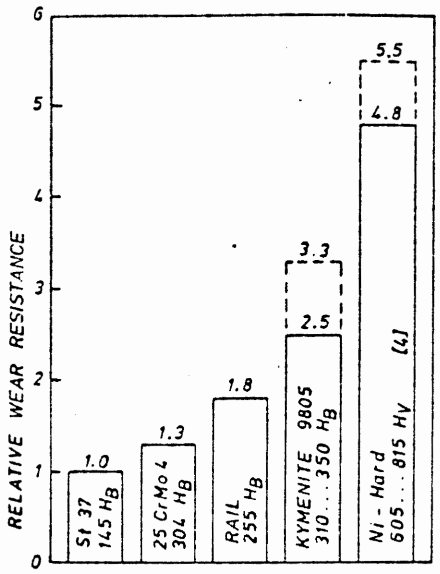


Fig. 10
Relative wear resistance of different materials in quartz sand

The gear wheel tests have also shown the reliability of K-9805 in emergency cases. If the lubrication temporarily fails the graphite together with oil is enough to lubricate the gear wheels until the disturbance in the lubrication has been cleared.

3.5
Machinability

It is essential for the succesful machining of work hardening materials that the cutting speed is suitably low and the chip thickness enough so that the edge of cutter works under the layer work hardened while cutting the previous chip. Several work phases can be accomplished prior to the final heat treatment because the transformations it causes are minimal. TiC tool inserts (K15) are the most suitable for turning. The machinability of K-9805 when hobbed is equal to that of a high alloyed CrNi-steel.

4
K-9805 as gear material

4.1
Tests and methods

The studies were carried out by using test gear wheels in accordance with Table 1. The following load limits were determined in the tests:

a) The endurance limit for surface stress of the tooth flank K_D or the endurance limit for Hertzian stress σ_H and the S-N curve of Hertzian stress for limited durability endurance. The tests were carried out in a test bench where gear wheel of test material was as driven wheel and gear wheel of case hardened steel as driving wheel. The endurance limit is such a surface stress or Hertzian stress that the tooth flank endures when the number of cycles is $5 \cdot 10^7$ without the pitting exceeding the limit of 0.5 % (wheel and pinion together). The pitting is estimated by measuring the extent of the pits by a microscope.

		FZG-tests		Own tests			
		Pinion	Wheel	Pinion	Wheel	Pinion	Wheel
Number of teeth	z	27	34	33	65	22	48
Module	m	3	3	3,5	3,5	5	5
Pressure angle	α	20°		20°		20°	
Helix angle	β	0°		15°		0°	
Reference diameter	d	81	102	119,57	235,53	110	240
Tip diameter	d_a	87	108	129,22	244,56	124,33	254,69
Tooth width	b	10	10	45	45	20	20
Center distance		91,5		180		180	

Table 1 Dimensions of test wheels

b) The S-N curve of the bending strength of the tooth root as well as the bending endurance limit for tooth root stress haven been determined by a tension-compression-pulsator. The test wheels are between the jaws of the pulsator so that the load passes the base circle at a tangent.

c) The static bending strength of the tooth with a tension machine and the impact strength with a pendulum hammer.

4.2
Results of tests made by Forschungsstelle für Zahnräder- und Getriebebau (FZG) of Technical University in Munich

The following test results are based on the tests carried out in Forschungsstelle für Zahnräder- und Getriebebau (FZG) of the Technical University in Munich in the beginning of 1976 under the guidance of Dr.-Ing. Heinz Rettig.

4.2.1
Endurance limit for surface stress

In regard to pitting the endurance limit for surface stress K_D or for Hertzian stress σ_H mostly at the pitch circle is used as basis when dimensioning the gear wheels. Under the test conditions the static surface stress is:

$$K_{DStat} = \frac{P}{2b}\left[\frac{1}{\varrho 1} + \frac{1}{\varrho 2}\right] = 2.86 \cdot \frac{\sigma^{2}_{HStat}}{E} \qquad (1)$$

by using the FZG-test wheels in Table 1:

$$K_{DStat} = 0.715 \cdot U \quad \left[Nmm^{-2}\right] \qquad (2)$$

$$\sigma_{HStat} = 216 \cdot U \quad \left[Nmm^{-2}\right] \qquad (3)$$

U = Force per face width $\left[Nmm^{-1}\right]$

When determining the endurance limit for surface stress K_{DTot} the following factors should be taken into account:

- number of cycles $N = 5 \cdot 10^{7}$
- the effect of additional dynamic loads under the test conditions, the effect of elastic transformations and inaccuracies (K_{Ddyn})

$$K_{DTot} = K_{DStat} + K_{Ddyn} \quad (\sigma_{HTot} = \sigma_{HStat} + \sigma_{HDyn}) \qquad (4)$$

- statistical reliability of 90 %

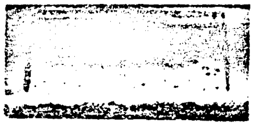
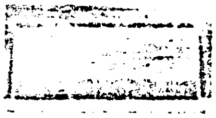
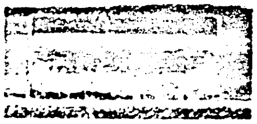
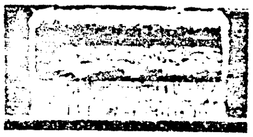
K_{DStat} Nmm^{-2}	 28.6	 33.6	 35.1	 41.5
Number of cycles	100×10^{6}	84×10^{6}	3.5×10^{6}	3.9×10^{6}

Fig. 11 Pitting typical in gear wheel of material K-9805

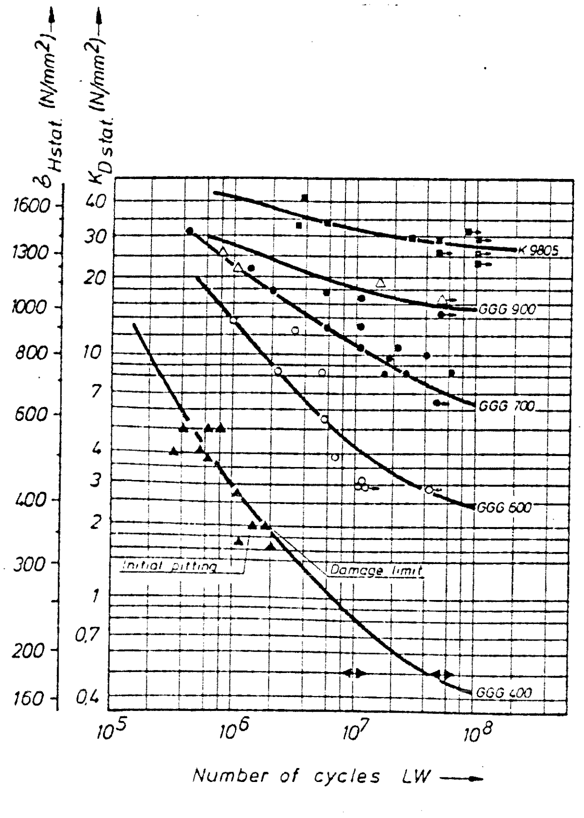


Fig. 12
Gear wheels of nodular iron GGG400...900 compared with K-9805. GGG900 and K-9805 tooth's profile ground, others finished by hobbing. Effective base pitch error f_{ew} = 15 um, n = 3000 mm-1, mild oil ν_{50} = 100 cSt/50°C

In figure 12 the S-N curve of static surface strength of K-9805 obtained in the tests is compared with the S-N curve of the corresponding well-known nodular iron grades. The results are of significance when the effect of the additional dynamic loads is also taken into consideration (fig. 13).

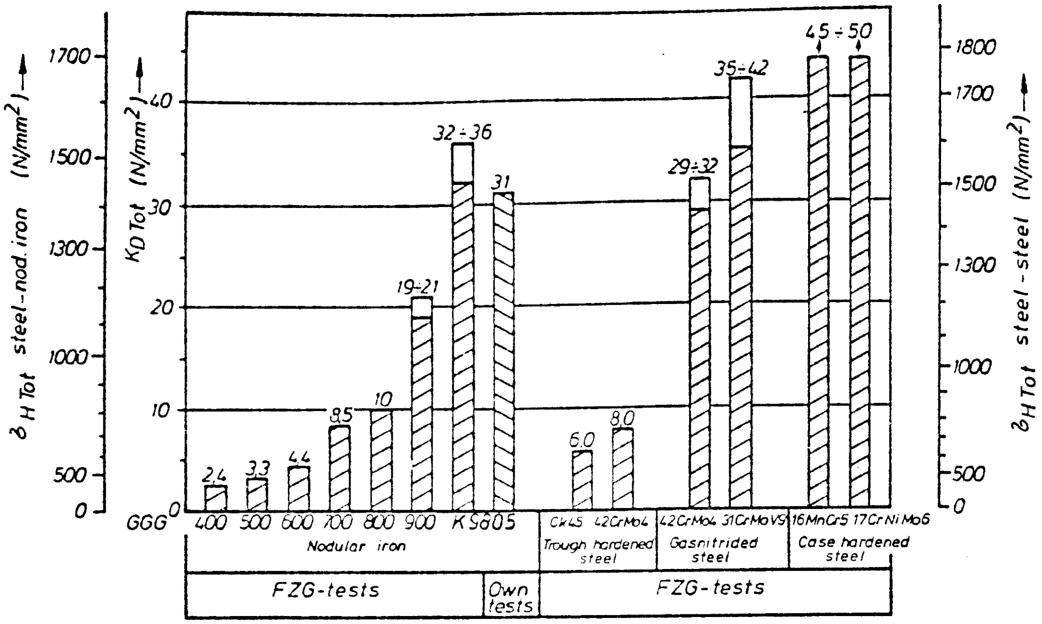


Fig. 13 Comparison between endurance limit for surface stress of different gear materials

The endurance limit for surface stress of K_D = 8.5... 10 Nmm^{-2} obtained with pearlitic nodular iron grades GGG700 and 800 (hardness 250...280 H_B) exceeds the corresponding values of the alloyed, quenched and tempered steels (42CrMo4, 50CrMo4, etc.) used in gear wheels. Even though the hardness of the austenitic-bainitic nodular iron K-9805 is equal to that of GGG900 (H_B = 290...350), the endurance limit for stress of K_D = 32...36 Nmm^{-2} was obtained. As to performance, K-9805, in the first place, competes with flame and induction hardened as well as with gas nitrided steels.

4.2.2
Bending endurance limit for tooth root stress

The test gear wheels were installed in the tension-compression pulsator (4.1 b) the stress being pulsating (preload P_v = 2000 N). The comparison-bending stress of the tooth root is calculated from the formula:

$$\delta_v = B \cdot z_1 \cdot q = z_1 \cdot q \cdot \frac{P \cdot \cos\alpha}{b \cdot d_{b1}} \qquad (5)$$

The tooth strength factor q is determined by taking into account the bending, compression and shearing stresses. The critical section is defined by the contact points of 30° tangents drawn at the fillet radius like in the ISO- and DIN-methods. For the FZG-test wheels of Table 1 the bending stress is:

$$\sigma_V = 0.511 \cdot U \quad [\mathrm{Nmm}^{-2}] \qquad (6)$$

U = Force per face width Nmm^{-1}

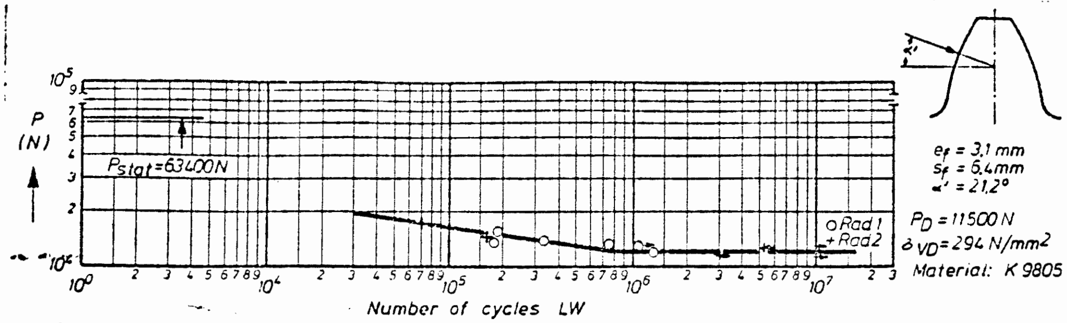


Fig. 14 S-N curve of bending fatigue strength for tooth root stress of pulsator tests

Figure 14 shows the S-N curve of the test material. The endurance limit for tooth root stress for the material K-9805 is σ_{VD} = 294 Nmin^{-1} (10 % probability of damage). When the probable durability is statistically 99 %, the corresponding value is σ_{VD} = 275 Nmin^{-2} (fig. 7). Figure 15 shows the comparison between the endurance limits for tooth root stress obtained (10 % probability of damage) and the corresponding values of other gear materials. K-9805 is on the same level with the alloyed, quenched and tempered steel 42CrMo4. From figure 7 it can be concluded that by shot peening K-9805 better endurance limits can be reached than for case hardened steel (σ_{VD} = 500 Nmin^{-2}).

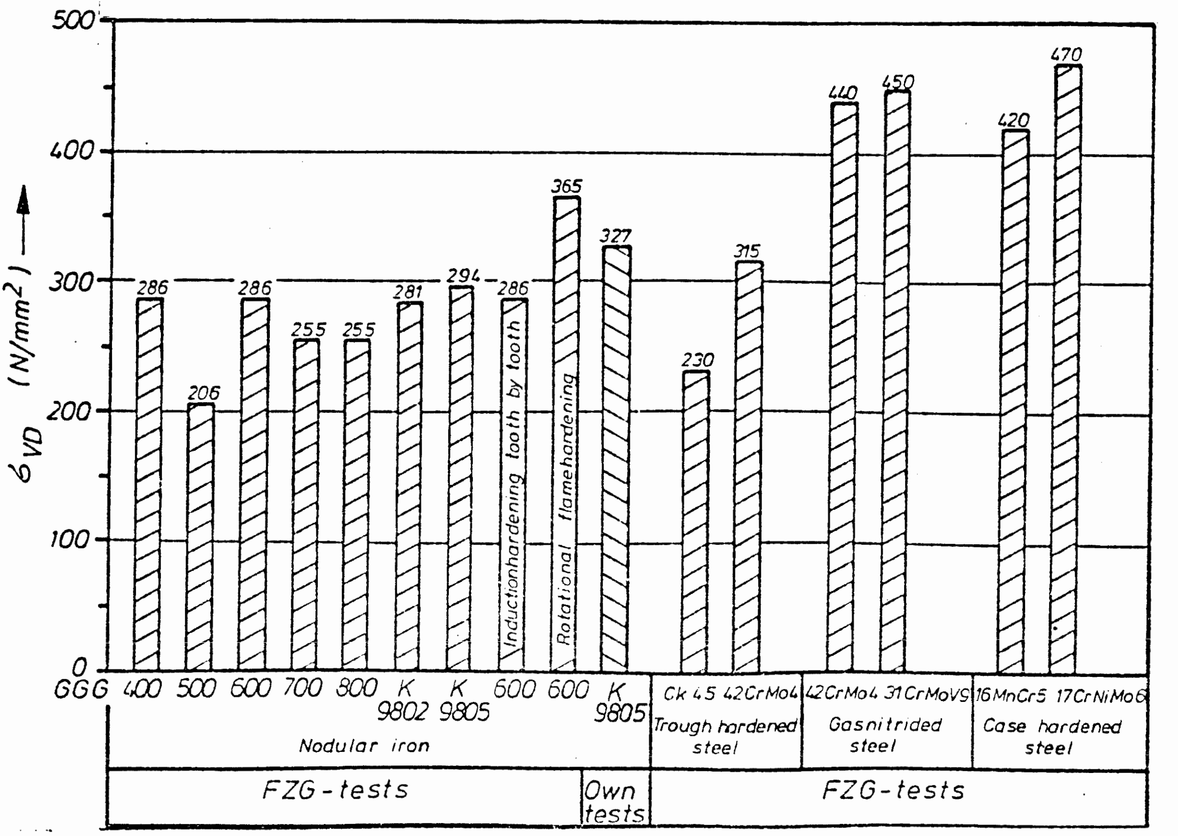


Fig. 15 Endurance limit for tooth root stress of different gear materials

As a result of the considerably lower notch sensitivity of the nodular iron grades compared to steels the tooth fillet radius affects the endurance limit for tooth root stress only slightly, even when using the traditional nodular iron grades (fig. 16). As to the austenitic-bainitic grade K-9805, the effect is even slighter.

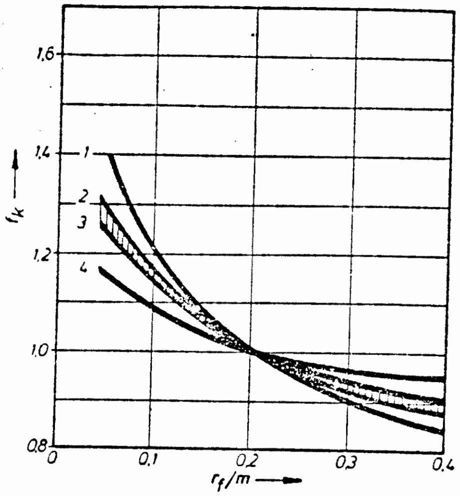


Fig. 16
Influence of tooth fillet radius $r_{f/m}$ to relative notch factor.

Curve 1: quenched and tempered steels
Curve 2-3: case hardened steel
Curve 4: cast materials

4.2.3
Static tensile strength and impact resistance of the tooth

In addition to the fatigue strength, the static tensile strength as well as the impact resistance of the tooth are of significance, because they indicate the ability of the gear wheel to carry overloads.

The static tooth root strength corresponds to the left side horisontal part of the S-N curve. The test results are shown in figure 17. In this respect, the grade 9805 is also able to reach the values of the case hardened steels.

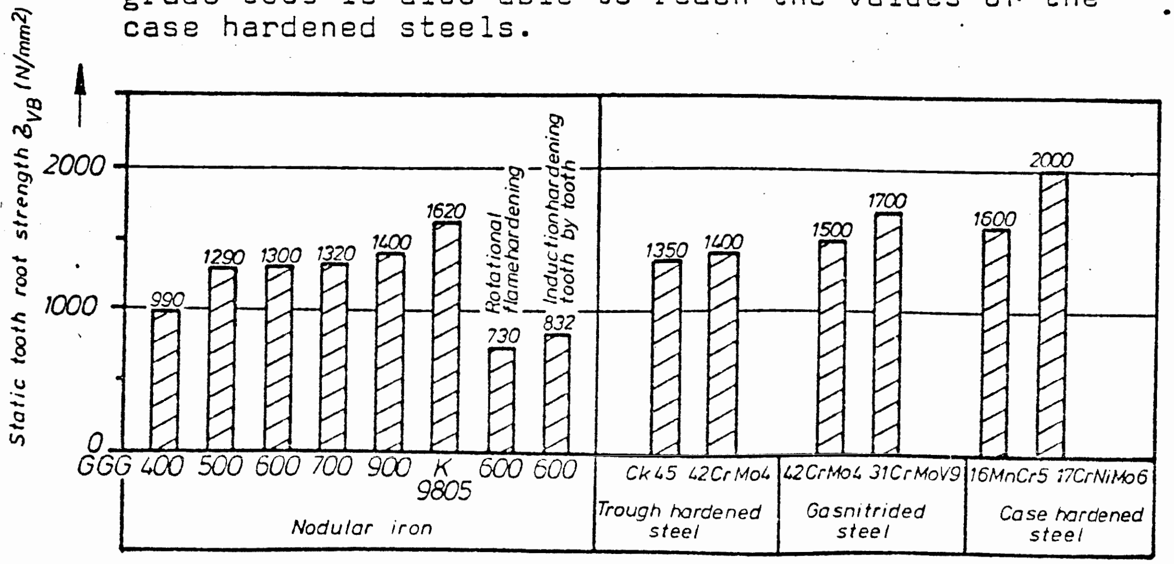


Fig. 17 Static tooth root strength of different materials

The results of the impact resistance tests of the tooth are shown in figure 18. The impact resistance of K-9805 is even better than that of case hardened steels but considerably lower than that of both quenched and tempered and nitrided steels.

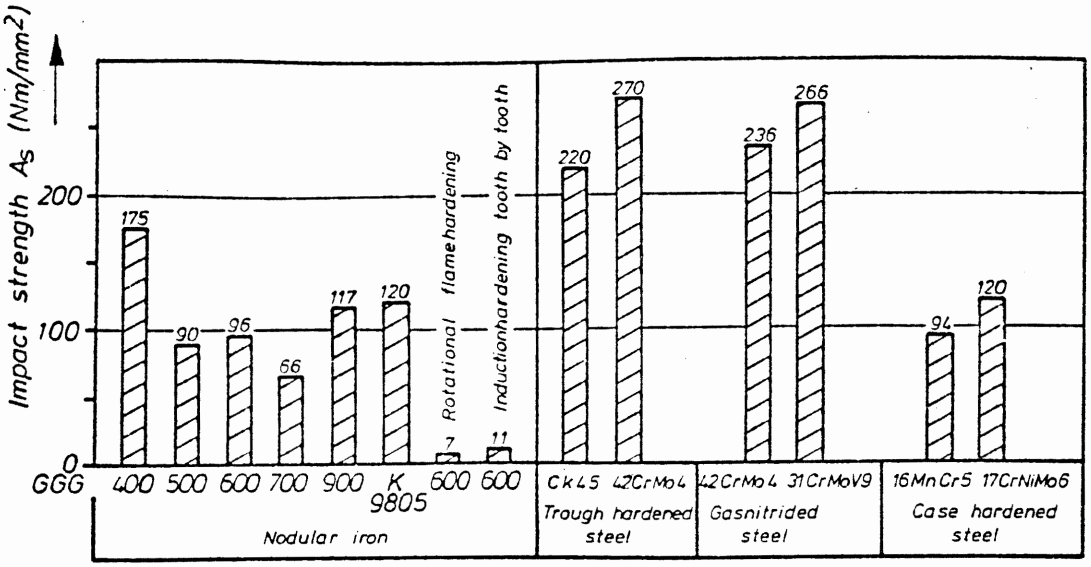


Fig. 18 Tooth root impact strength of different materials

4.3
Results of own tests

Santasalo's own gear wheel tests have mainly been carried out with test wheels according to Table 1. The endurance limit for tooth root stress is determined by pulsating tests. Running tests are used for checking the pulsating tests and determining endurance limit for surface stress. The results are evaluated according to the calculating method in use, taking the desired statistical reliability into consideration. The running tests are carried out using Santasalo's own test benches, out of which two are for spur and helical gear wheels (center distance a = 180) and one for bevel gear wheel (reference diameter for bevel wheel is 200). The results we have obtained in regard to both the endurance limit for surface stress as well as for tooth root stress are very close to the values given by the FZG-tests (figure 13 and 15). Figure 7 clearly shows how by using this work hardening material with shot peening the corresponding strengths of case hardened steels can be obtained.

The results given for K-9805 are based on those of appr. 300 pairs of spur and helical gear wheels (K-9805/15CrNi6) and 40 pairs of bevel gear wheels (17CrNiMo6/K-9805), tested since 1971.

5
Applications of the austenitic-bainitic nodular iron

5.1
The most important properties

As a conclusion on the basis of the above presented studies it can be stated that the most important properties of the austenitic-bainitic nodular iron K-9805 as gear material are:

- The good static and dynamic strength values together with the low notch sensitivity and sufficient toughness provide excellent dimensioning strength. The work hardening property results in the possibility of improving the endurance limit for tooth root stress considerably by shot peening.

- As a result of the excellent endurance limit for surface stress it is possible to use this material as a substitute for flame and induction hardened gear materials, expecially when large dimensions are concerned. Since the teeth need no surface hardening and grinding, the production is considerably simpler and less expensive.

- The pitting of the nodular iron grades differs from that of steels in that the pits are small and evenly devided above and below the pitch circle. The increase in the number of pits, when the number of cycles corresponds to the endurance limit for surface stress, is almost proportional to the number of cycles. Since the pits remain small, they do not damage the tooth flank but only increase wear.

  Even with loads greater than the endurance limit for surface stress indicates, the pitting damages remain insignificant compared to steel wheels. Consequently, the damage line of pitting follows the S-N curve very closely, which, in turn, indicates that the material endures overloading relatively well.

- The surface roughness does not greatly influence the load carrying ability of the tooth flank. The difference between the endurance limit for surface stress of a ground and hobbed tooth is less than 15 %; the corresponding difference in regard to other nodular iron grades amounts to appr. 30 %. As to steel gear wheels, the difference is over 15 %, depending on the surface roughness and the strength of the material. The fact that the influence of the surface roughness is so insignificant is mainly due to the lower notch sensitivity of the material. Furthermore, the running-in properties of the surface are excellent, from which follows that the surface relatively soon becomes smooth while running and the hydrodynamic part of the lubrication increases.

- The tests have also shown that the friction coefficient regarding the range of boundary lubrication is smaller than that of steel gear wheels. Of essential importance is the work hardening of the surface which is most intensive just at profile peaks.

Since a considerably lower surface roughness can be obtained with this material (same machining values) than with steel by hobbing, it will suffice if the teeth are finished by hobbing.

- The vibrations are damped about 40 % faster than in a steel construction, which among other things, lowers the noise level.
- The reliability in emergency cases is an important factor from the user's point of view. This means that the lubrication disturbance does not damage the teeth immediately but they endure the exceptional situation relatively well. The graphite present here is of essential contribution.
- Owing to the stability of the retained austenite the suitable working temperature range is very wide, from -80° to +200°C.

5.2
Applications

The austenitic-bainitic nodular iron K-9805 was originally developed as design material for gear wheels. This is why the Santasalo-Transmission has introduced a new component standardized gear series into the market. The design of this series is based on utilizing the properties of K-9805. The ratio range of the gear series is i = 1...1000 and maximum output torque appr. 600 kNm.

By using K-9805 in vechicles as gear wheels a better durability than with case hardened steels has been gained, due to the high resistance of shock loads.

As different rail wheels, e.g. in mine carts, multiple service life has been gained by using K-9805, compared to the flame hardened steel that was used before. The experiences are similar also in the rail wheels of converters and other ore handling equipment. Cold working is of essential importance in the applications.