Large Pinions for Open Gears: The Increase of Single Mesh Load

Michel Pasquier and Fabrice Wavelet

This paper introduces mandatory improvements in design, manufacturing and inspection—from material elaboration to final machining—with special focus upon today's large and powerful gearing.

Introduction

This paper is based on the fact that mining mills are becoming more and more powerful—up to 8,500 kW per pinion. Then the pinions have to grow to meet the single-mesh power increase and, consequently, conventional manufacturing and inspections reach their limits. Therefore the methods that have been used successfully for years must improve. Indeed, most customers have already acknowledged this need in the requirements of their technical specifications.

Starting from rough material and ending with final inspections, the intent of this paper is to introduce the needed technical improvements in manufacturing and inspection of large pinions to achieve the required transmitted power and the related service factors, as defined by worldwide consensus standard ANSI/AGMA 6014–A06.

Gear Rating According to ANSI/AGMA 6014–A06

The rating principle of a large pinion in an open gear set—according to ANSI/AGMA 6014–A06—is defined by its possibility to transmit a certain power, considering a certain safety factor—both in terms of bending strength and pitting resistance.

ANSI/AGMA 6014–A06, Equation 14:

$$P_a = \text{the lesser of } \frac{P_{acm}}{C_{SF}} \text{ and } \frac{P_{atm}}{K_{SF}}$$

where:

P_a is transmissible power

C_{SF} is safety factor for pitting resistance

K_{SF} is safety factor for bending strength

Considering now ANSI/AGMA 6014–A06 formulas to determine P_{acm} and P_{atm}:

$$P_{acm} = \frac{\pi n_p F}{396{,}000} \, \frac{I}{\boxed{K_{vm}}\boxed{K_m}} \left(\frac{d \boxed{s_{ac}} Z_N C_H}{C_p} \right) \tag{1}$$

$$P_{atm} = \frac{\pi n_p d}{396{,}000 \boxed{K_{vm}}} \, \frac{F}{P_d} \, \frac{J \boxed{s_{at}} Y_N}{\boxed{K_m} K_{Bm}} \tag{2}$$

Circled above are the parameters having the most influence on the final results:

K_{vm} (dynamic factor) and K_m (load distribution) are directly related to tooth accuracy

S_{ac} (pitting fatigue limit) and S_{at} (bending fatigue limit) are purely dependent upon material

Their definition and actual results condition the service life. In other words, the control of the manufacturing and inspection parameters that make these criteria are of the most importance.

Material

Material is of great importance to service life, but is also of great importance in terms of design. Let's consider an open gear set designed to transmit a power of 7,000 kW (9,387 hp) using a steel pinion, case-hardened:

- Grade M1 (low quality): $K_{SF} = 2.77$; $C_{SF} = 2.21$
- Grade M2 (best quality): $K_{SF} = 3.10$; $C_{SF} = 3.02$

In the case of large pinions, achieving the required mechanical properties throughout the entire part is a challenge. Thus perfect control of the manufacturing process and quality assurance—from ingot casting to final heat treated forging (including case-hardening)—is mandatory, which is the central reason that the M2 material is chosen.

Rough material. The pinions are manufactured from forged parts, themselves coming from an ingot. The ingot casting requires high technical skill to achieve both the metallurgical requirements (mechanical properties, homogeneity, etc.) and other parameters known for their influence on the behavior of the part in service (cleanliness, compactness. etc.).

Ingot casting. Some of the key parameters in respect to fatigue behavior of the parts are obtained from the casting and will not change afterward, e.g.:

- ***Soundness*** is the absence of macro-defects like porosities or cracks
- ***Cleanliness*** is the absence of endogen, non-metallic inclusions and segregation
- ***Homogeneity of microstructure*** through the entire thickness
- ***Uniformity of secondary structure*** (grain, etc.)
- ***Chemical composition*** is an adequate and controlled quantity of alloy elements such as manganese, chromium, nickel, copper, molybdenum and vanadium

The following is a review of the parameters:

Segregation. Even though it is not a standard requirement, the first point relevant to the solidification process is the segregation. Segregations are a localized over-abundance of alloying

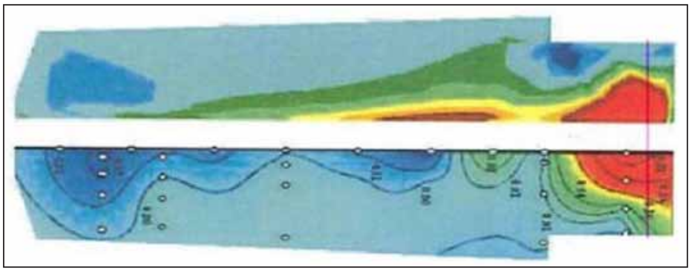


Figure 1—Computer simulation of segregation.

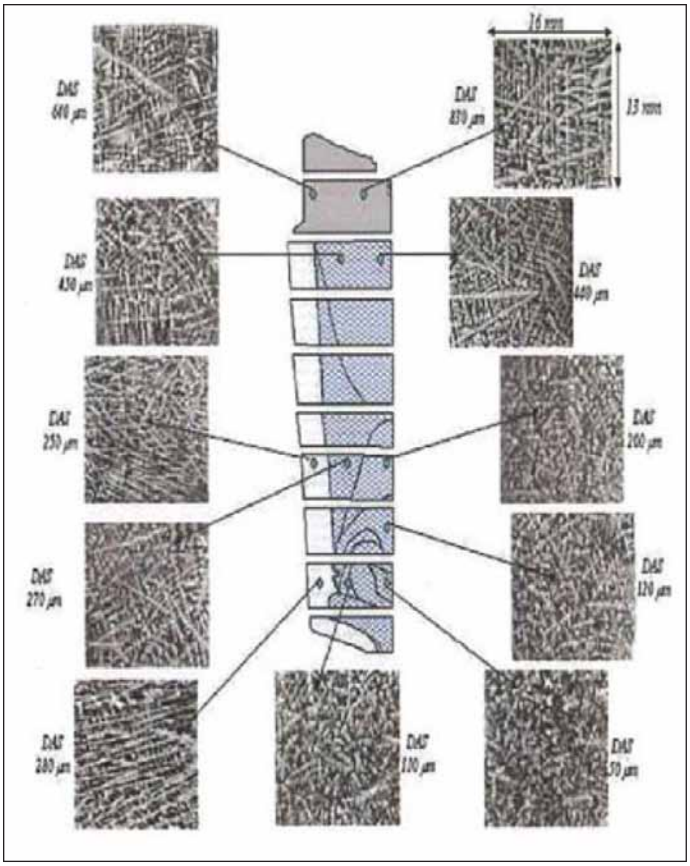


Figure 2—Actual segregation in ingot.

Figure 3—Sudden breakage due to hydrogen embrittlement.

Figure 4—Magnification of hydrogen burst in the broken surface.

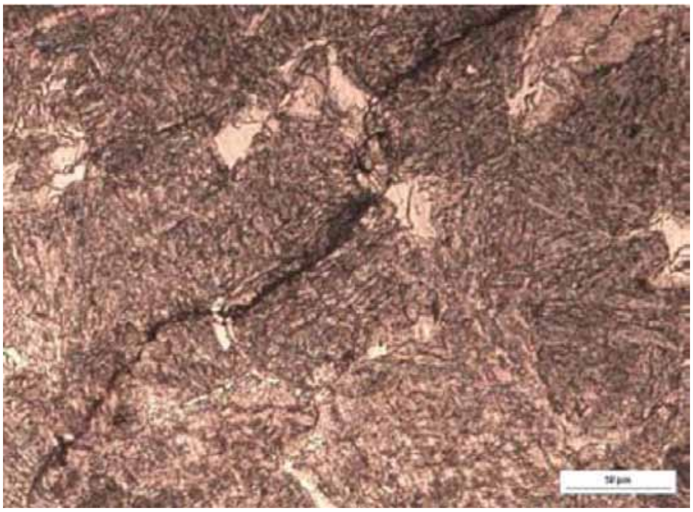


Figure 5—Free hydrogen influence—microcrack formed during forging.

elements, implying a decline in mechanical and fatigue properties that may lead to shrinkages. As heat treatment cannot erase such segregations, it must be avoided. With technology development and solidification knowledge, solidification can be more accurately computer simulated. Some ingots have very low levels of segregations, even for large castings (Figs. 1 and 2).

Cleanliness. Cleanliness is at the top of metallurgical standard requirements for obvious reasons; i.e., cleanliness is related to non-metallic inclusions—even though they are needed to initiate solidification and to obtain a thin and homogeneous structure. A local concentration of these elements will lead to buried defects. A definition of the acceptance criteria is then needed, but the problem is that cleanliness can be stated according to several different standards for different results. For example: in ANSI/AGMA 6014–A06 the cleanliness requirement is according to ASTM866 or AMS 2301. ISO 6336 refers to ISO 4967. Sometimes, steel manufacturers rate cleanliness in accordance with DIN 50 602, Method K. Are we then to consider only ANSI/AGMA 6014–A06 cleanliness requirements for steel pinions meant for the teeth area (Table 5, Note 2), while case-carburized pinions have different requirements (Table 7, Item 4)?

The multiplicity of standards, and of course their respective acceptance criteria, makes it almost impossible to determine an appropriate content for the different kinds of non-metallic inclusions (sulphides, aluminas, silicates and oxides). For the large parts we are talking about, cleanliness shall be achieved throughout the complete thickness.

H2 content. Even though it has long been evident that free hydrogen content is of the greatest importance, none of the existing rating standards defines a maximum content. Free hydrogen may have a dramatic effect on the part, whether at the manufacturing stage or during service. As the hydrogen content increases, the internal gas pressure increases at an exponential rate. Combined with inherent material dislocations and atomic diffusion (embrittlement is a very complicated process), hydro-

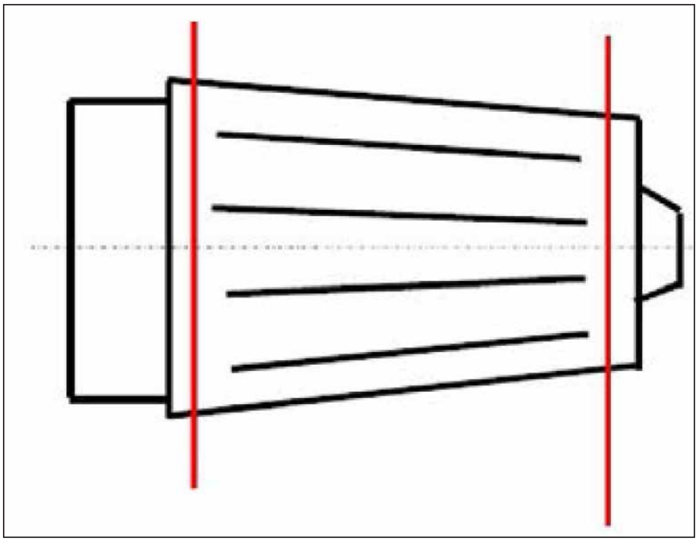


Figure 6—Ingot location of head and foot cuts.

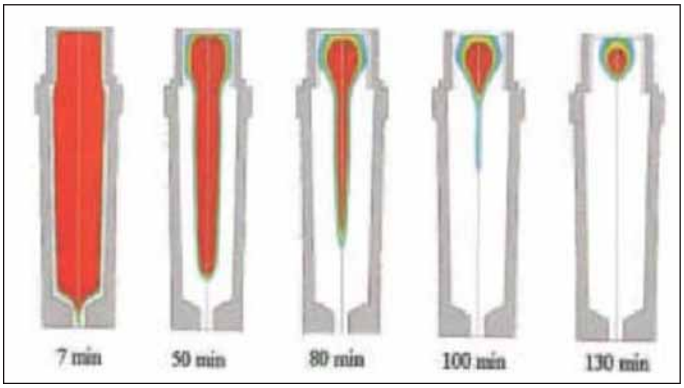


Figure 7—Computer simulation of cooling.

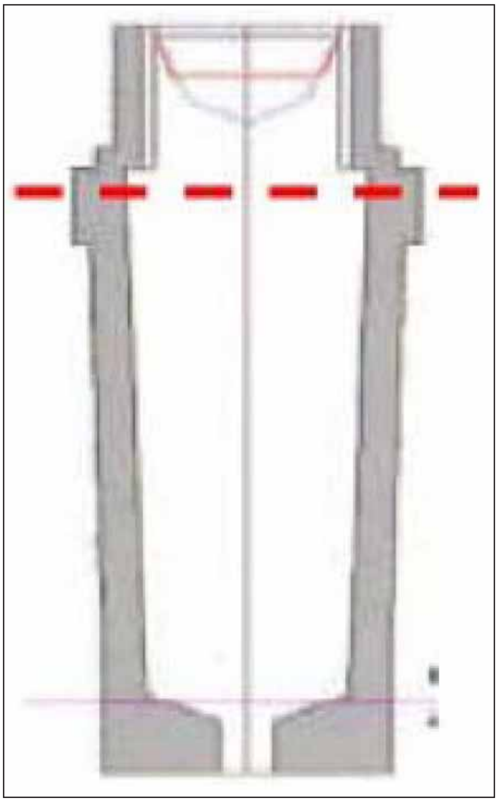


Figure 8—Location of the porosities in the ingot.

gen may lead to severe damage. A well-known effect of that, and probably the most typical, is a sudden break while efforts undergone by the part are very low (Figs. 3–4). Another effect can occur during ingot casting or at the forging stage. Figure 5 shows a crack that occurred during forging, generated by hydrogen embrittlement in a bainitic structure.

The origin can be summarized as follows:

Steel Ingot →Dendrites → Segregations + Free H2 →
Embrittlement →Cracking

A solution to avoid such embrittlement is to maintain a low level of free hydrogen. This can be achieved with a vacuum degas process. By today's standards, 2 ppm of H_2 is a limit commonly reached and guarantees a minimum risk of embrittlement. But, naturally, then comes the question of the measurement of free hydrogen in such small amounts. Whatever the equipment used, the hydrogen content is better tested in the hot top (ingot casting) rather than via ladle analyses.

Forging. The second important step concerning rough material is forging; the ingot is cut head and foot (Fig. 6).

The key point is the location where the initial piece is taken from the ingot. Figure 7 explains the cooling process of the ingot and the final location of porosities (in the top). If the initial piece is taken close to the head of the ingot, it should be carefully checked that the head cut is enough to remove all porosities (Fig. 8). An example of defect found in a large pinion forging is shown in Figure 9. Small cracks or very small cracks were observed in the core of the forged part. The origin of the defect can be ascribed to the location of the initial piece close to the top of the ingot (last solidification area), where important areas of porosity are present (Fig. 10).

Under constraints (thermal, mechanical), porosities turn into cracks. By avoiding this area of last solidification when cut, the ingot is absolutely needed to obtain a quality product. For forgings, it is expected to achieve a certain reduction ratio (commonly 3:1). What does this mean for pinions, and specifically for large parts in the teeth area? Reduction ratio means the difference in terms of diameters between the ingot and the wrought piece. Forging reduction induces a compactness improvement and a structure orientation that are both good for mechanical properties.

Considering the volume represented by a large pinion, and the increased influence of segregations, porosities, hydrogen, etc., and due to its size, the use of wrought product with a high reduction ratio is obviously of more importance for small pinions.

Inspection

ANSI/AGMA 6014–A06, as well as the customer's technical specifications, often include some inspection requirements and acceptance criteria for the abovementioned key parameters. Whatever they are, the most difficult inspection regards internal material soundness through ultrasonic (UT) inspection and its related acceptance criteria.

ANSI/AGMA 6014–A06 (Tables 5 and 7) give both test conditions ("For pinions, above UT applies in radial direction, 360 degrees around, and axially from both ends") as well as acceptance criteria. The concern comes with the ultrasonic inspection that is to be repeated after carburization (for case-carburized pinion)—i.e., anything different from the initial test is to be recorded, which is quite imprecise and difficult in practice.

For this reason some specific requirements for through-hardened and case-carburized pinions have been developed in recent years. This includes both test methods and highly stringent acceptance criteria, based on the fact that with products being bigger and more powerful, any single problem could lead to dramatic effects. Concerning through-hardened pinions, only one test is carried out at the rough-machining stage. For case-carburized pinions, two inspections are carried out: 1) at the rough machining stage; and 2) after case-carburizing and final grinding.

UT inspection is done on machined surfaces with a surface finishes equal to Ra 6.3 μm (160 micro-inches) or less, which is even better than required in ANSI/AGMA 6014–A06. Inspection is performed by either using reflection on calibration blocs (AVG method) or the DGS/CAD method (automatic calibration); straight-beam probes of two MHz or less are used. 100% of the pinion's volume is tested in the radial direction on the major diameters; in addition, the pinion is inspected lengthwise from each shaft end. This last test provides a good idea of the material quality—even if this is not part of the acceptance criteria. Using a 2 MHz probe, shoot from one shaft end; should you:

- Obtain one back-wall echo with a loss less than 30% = what's expected
- Obtain two back-wall echoes in the same conditions = good forging
- Obtain three back-wall echoes = excellent forging

Even though more restrictive acceptance criteria have been defined, the available feedback does not conclude whether these requirements are correct or perhaps even too conservative.

A well-known method common in the medical field is now currently under development for industrial applications—phased-array ultrasonics (PAUT). This new technology, applied to steel forgings, may bring a new level of interpretation for expertise purposes (Figs. 11 and 12).

Phased array probes typically consist of a transducer assembly containing from 16 to as many as 256 small elements that can each be pulsed separately. In its most basic sense, a PAUT system uses the wave physics principle of phasing. A certain volume of the part is swept individually by each ultrasonic element, with a very brief delay between each. Electronic interpretation of the signal provides 2-D mapping of the section tested.

As far as the strength and integrity of forgings are concerned, the PAUT method provides new levels of information and visualization as compared to common UT inspection. Yet, it remains an ultrasonic technology, meaning phased-array ultrasonics will still imply different directions of shooting to determine the exact volume of a buried indication. The accuracy and visualization introduced by this continuously improving technology—coupled with the possibilities and limits extant in today's electronics—render PAUT a significant inspection tool upgrade over traditional UT.

Microstructure:

Through-hardened steels. Through-hardening is the most common treatment for the heavy parts discussed here; hardness requirements are 340–400 HB. Nevertheless, quenching in an adequate bath and tempering must also be conducted in order to ensure that the required microstructure is achieved in the core of

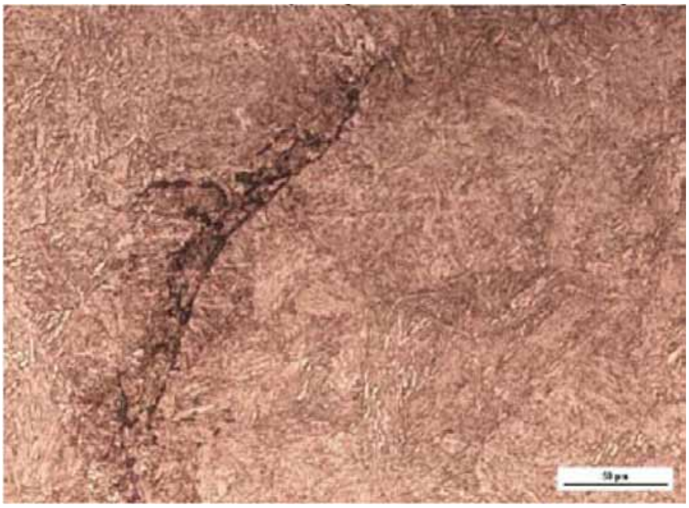


Figure 9—Crack in a forged part formed from a porosity.

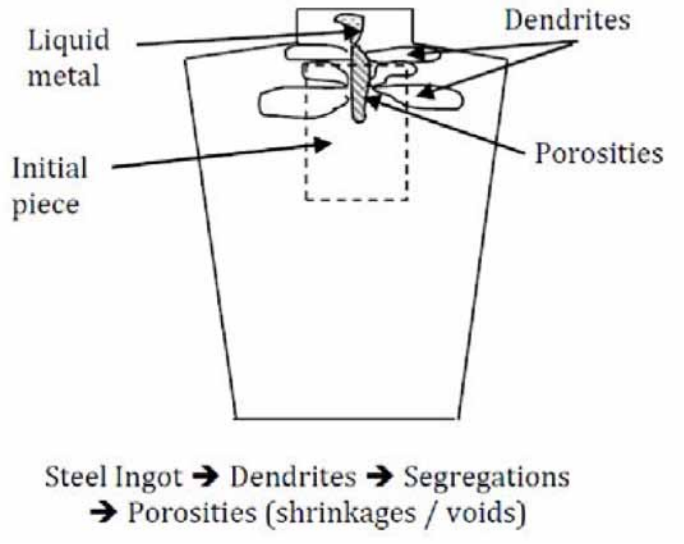


Figure 10—Example of initial part location of a failed forged.

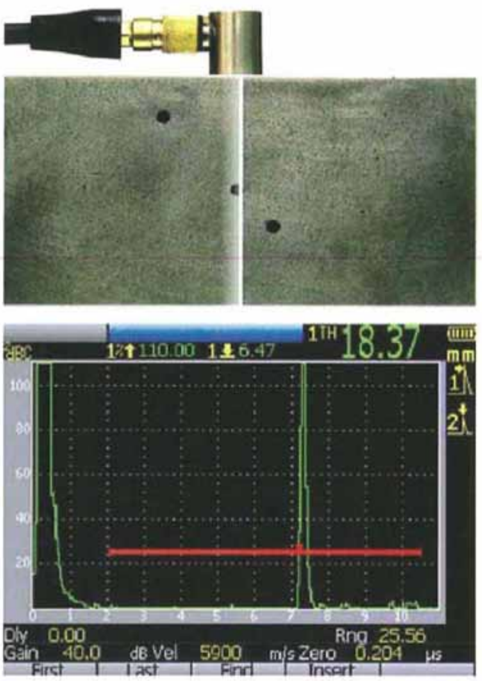


Figure 11—UT inspection—basic principle.

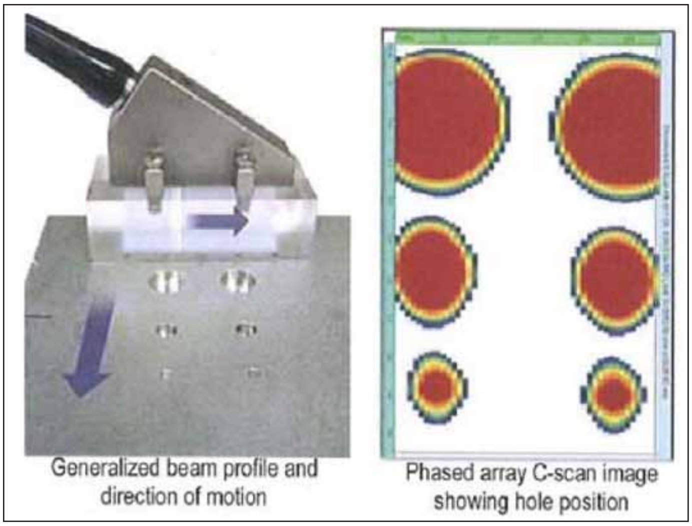


Figure 12—Phased array inspection—basic principles.

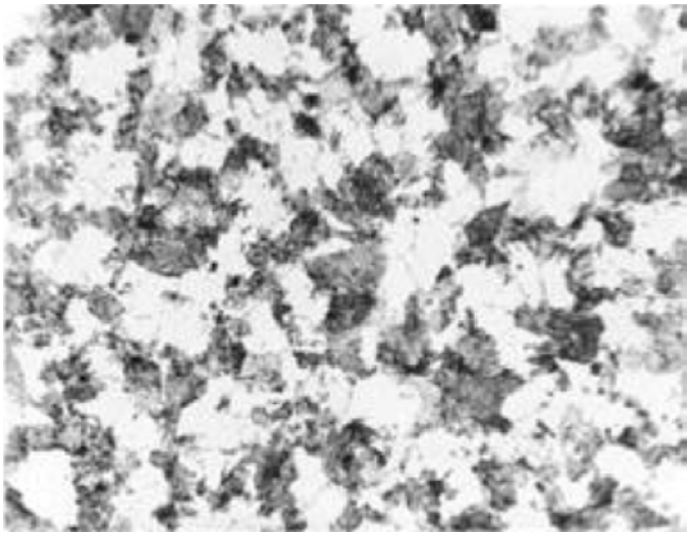


Figure 13—Case carburized steels—+TH initial microstructure.

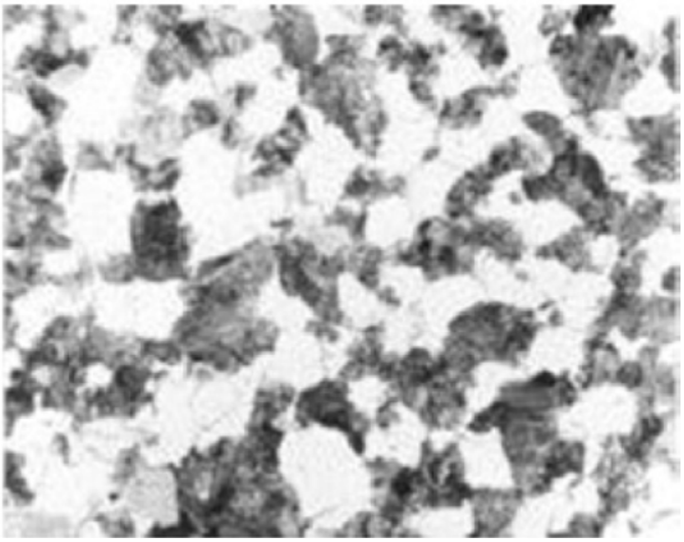


Figure 14—Case carburized steels—+FP initial microstructure.

the part. And even if bainitic structure is required (for very large parts), a given amount of martensite and/or residual austenite is acceptable in the core—where the stress in service is very low.

Case-hardened steels:

The initial microstructure of case-hardened steel is of the greatest importance in respect to final distortion after case carburizing and quenching. It is related to delivery conditions as defined in EN 10084 (although current American standards do not list a corresponding material, and mainly use 18 CrNiMo 7–6). The most common microstructures are:

Annealed with a range of hardness: (+TH). It is a softening treatment according to EN 10052. The intent is to reduce the hardness of the material to a given range (around 200 HB). The annealing process is:

Austenitization to a temperature slightly above AC3 for a 18CrNiMo 7–6 steel

Slow cooling

The resulting microstructure is composed of ferrite and pearlite; but other microstructure elements, such as bainite, can be found as well. Structure is inhomogeneous (Fig. 13) and thus generates final deformations after case-carburizing, which cannot be monitored.

Treated to achieve a ferritic/pearlitic structure with a range of hardness—(+FP): From an historical point of view, it is the bainite— or "Behandelt auf Ferrit–Perlit Gefüge (BG)" treatment cycle, according to DIN. A typical BG cycle for 18CrNiMo 7—6 is:

- Normalization at 930°C (1,700°F)—(holding time: 1 min/mm [1 min/0.04"] +1h30)
- Austenitization at 840°C (1,540°F) followed with oil or polymer quenching
- Tempering at about 650°C (1,200°F): (holding time 2 min/mm [2 min/0.04"] +2h)
- Hardness: around 180 HB

The ferritic/pearlitic structure is homogeneous (a so-called "checkerboard" structure; Fig. 14) and provides good results in respect to residual deformations post case- carburizing.

Even if such a structure is not defined in EN 10084, strategic parts can be requested with an initial microstructure—"Quenched and Tempered," +QT. Generally, it is bainitic quenching followed by tempering. The bainitic structure is more homogeneous and, despite the case-carburizing temperature being above AC3 and the initial microstructure being withdrawn, residual deformations are minor and homogeneous.

Manufacturing

One of the simplest ways to increase power transmitted through mesh is to enhance the tooth accuracy level. With a gear set of AGMA Q8–Q10 (gear – pinion) from a few years ago, the gearing now requires AGMA Q10–Q12. These modifications allow a substantial gain on the dynamic factor, although only gear accuracy is considered in the calculations through ANSI/AGMA 6014–A06 (K_{vm}; see Equations 1 and 3). Specifying enhanced accuracy levels in the drawing is one thing; meeting them on the shop floor is another story.

Machining

Cutting. Although the CNC machine offers a high accuracy, pinion accuracy (lead, pitch, profile mainly depends on the tool itself. In terms of cutting, errors transmitted by the machine compared to errors given by the tools have an influence from 1 to 10. Of course, the cutting mode (single index vs. hobbing) introduces a different set of deviation, some more pronounced on pitch for single index and others more pronounced on lead for hobbing, to make it simple.

Different processes are available to prepare pinions to be ground with different benefits and disadvantages:

- Small pinions (i.e., 19 teeth, 25.4 module) can be fully turned and cut on the same machine, a five-axis CNC machining center. Since the shaft and teeth are geometrically related, only one set-up is required. This avoids lack of accuracy during each setting on every machine. Moreover, the reference axis is kept all along the manufacturing, improving greatly the overall accuracy. In the other hand, machining of the teeth is done with conventional milling tools. Specific hobs or inserts are not required in those conditions. With such a machine, geometry of the teeth is as accurate as on gear cutting or gear grinding machines (Figure 15 and Figure 16).
- Large pinions (i.e., 19 teeth, 33.866 module) still have to go through a traditional process, where turning and cutting are separated. Today's pinion sizes and the wanted level of accuracy (AGMA Q12), however, impose the use of carbide tools. Good points are the cutting of hard materials (over 340 HB), the longevity (one set of inserts for the complete cutting), and of course, the quickness of cutting. The disadvantages are a restricted number of suppliers, the cost of such tools, which are mainly made on demand, and the fact that with each pinion being different, it requires the purchase of individual sets of inserts every time.

Grinding

After case carburizing, quenching and tempering, a large amount of distortions is present. Their anticipation during the rough machining process is a key point to guarantee the final tooth thickness combined with the required carburized layer thickness. The final tooth geometry, because of the hardened surface, imposes a need for tooth grinding. The most efficient process is form grinding (Figs. 17 and 18).

Load distribution over the face width is a key point in service, and with even more importance being placed on the increase of mill power, efficient grinding becomes more and more needed. Case carburized pinions are going through grinding as a normal process. It has to be pointed out that the grinding process is only flank grinding to avoid removal of compressive residual stresses in the root filet and to avoid surface tempering.

The benefits on through hardened pinions are also significant, especially when considering tooth corrections (on lead and/or profile). These corrections are planned to compensate elastic deformations to achieve the best possible load distribution during meshing. Such tooth modifications can only be addressed through a grinding process. In mining applications, with gearing designed according to ANSI/AGMA 6014—A06, such a correction is not taken into account and gives unrealistic longitudinal load distribution.

Figure 15—Pinion milling on multi multi-axes machine.

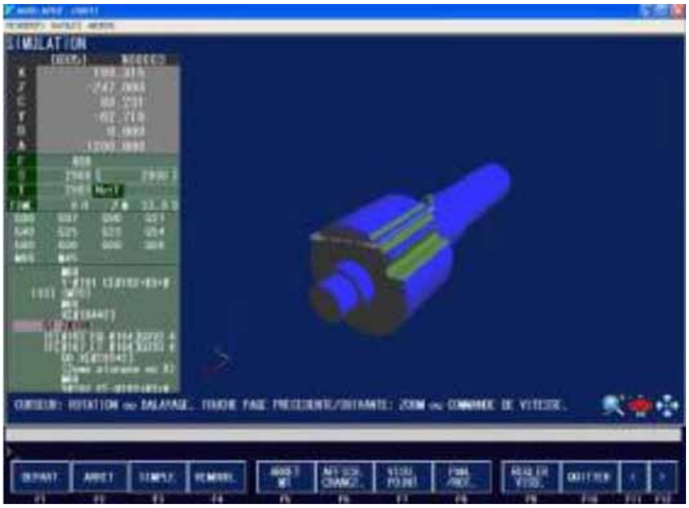


Figure 16—Pinion milling—CN software.

Figure 17—Large CNC form grinding machine.

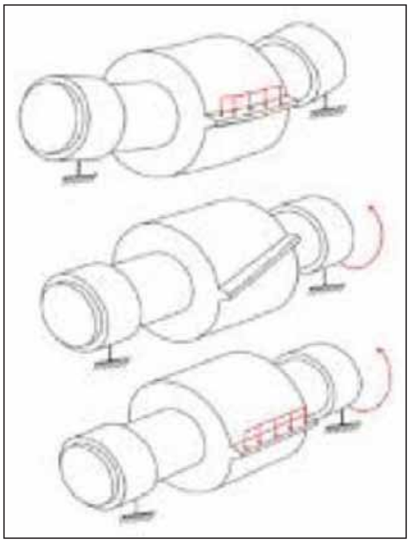


Figure 18—Computer simulation of torsional and bending deformation.

Inspection

Tooth geometry. Since the quality level is considered in the calculation of several factors in ANSI/AGMA 6014—A06, the geometry of the pinion teeth has to be verified to make sure that the service factors are actually achieved. This can be done either on heavy gear measuring machines, on the gear cutting machines or gear grinding machines.

Part size and weight makes the calibration of measuring devices difficult—there are no comparable "reference laboratories" and "reference masters" available. The calibration chain cannot be the same as for small parts. An inter comparison procedure has to be developed to accurately check the geometry of the teeth, with enough repeatability and reliability. On the other hand, because surface finish is of great influence on fatigue properties, the measurement of surface conditions, for both through hardened and case carburized pinions, requires high tech measuring apparatus (Figure 19).

Internal structure. Tooth internal fatigue fracture, TIFF, is a gear failure mode based on fatigue, not related to contact or bending failure mechanisms. Neither ANSI/AGMA 6014—A06 nor ANSI/AGMA 2001—D04 includes an assessment method for determining the susceptibility of gear failure under this mode, although it is known that some pinions have failed under loads which were below the predicted range of the rating procedure. In a TIFF failure, the crack initiates beneath the flank surface and propagates via fatigue modes both into the body of the tooth and towards the tooth surface. The result is a complete tooth break (Figs. 20, 21 and 22).

This kind of damage can occur on a case carburized pinion (Figure 23) after several thousand operating hours. The aim of ultrasonic inspection is to detect internal discontinuities as early as possible, and to check changes in the buried indications (if any) through the manufacturing by repeat inspection. UT inspection is performed on finish machined surfaces with a surface finish equal to Ra 6.3 µm or less (160 micro inches):

- 100% of the pinion's volume has to be tested using a straight beam probe
- In addition, pinion is inspected lengthwise from each shaft end.
- Inspection is carried out using straight beam probes with a frequency of 2 MHz or less.

Figure 19—CNC gear measuring machine for heavy parts.

Figure 20—Example of fatigue fracture initiated from involute part of the profile.

Figure 21—Magnification of one edge of the broken surface.

Figure 22—Magnification of the opposite edge of the broken surface.

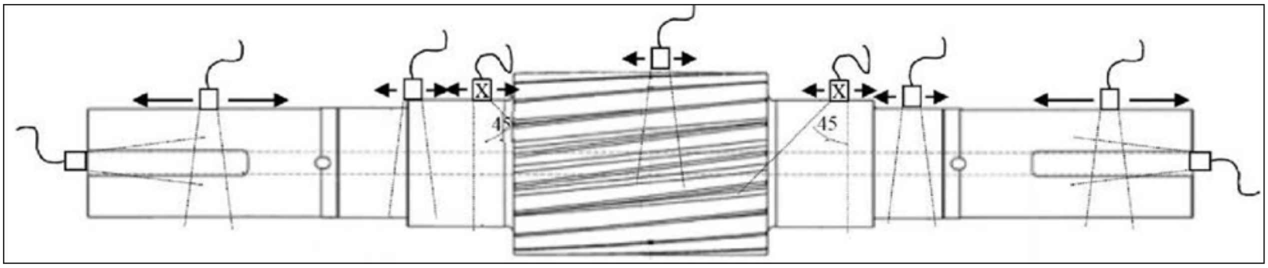


Figure 23—UT inspection: location of inspection areas and type of waves used.

- Inspection is completed with angle beam probes 45°, frequency 2 MHz or less, where a back-wall echo cannot be maintained.

Another method can be used—high frequency surface inspection using a straight beam probe of 8 MHz. The calibration procedure is rather complex. A calibration bloc made of the same material that has undergone the same heat treatments has to be used. A flat bottom hole of 1 mm is then drilled in this reference piece (Figure 24). With such a high frequency, the close surface can be checked on few millimeters in depth, i.e., just below the case depth or at the maximum shear stress depth.

Case-hardened layer. According to most standards, the case-hardened layer as well as the case depth, is verified on a coupon which undergoes all the heat treatments of the part itself. However, the coupon standard dimensions are not related to tooth dimensions, and thus the obtained results can be subject to discussion. To avoid such a discussion, a procedure was developed internally for the inspection of the case hardened layer and case depth, on the part itself. After final grinding, a sample is cut from one tooth edge, and due to case hardening deformations, this is where the maximum of the case hardened layer has been ground (Fig. 25).

Measurement of the case depth is made by a laboratory microhardness machine on a polished sample. All hardness marks should be aligned perpendicular to the flank within a 5 mm wide strip. The case depth corresponds to the depth where 550 HV1 is reached (Fig. 26).

A nital etching is then performed, and the actual microstructure of the case-hardened layer can be studied. As the surface of the teeth has been enriched with carbon and then quenched and tempered, this case- hardened layer should be made of tempered martensite. At the same time, presence of any carbide networks is checked as such a concentration can lead to an unexpected service failure (Fig. 27).

Grinding damages. As far as case carburized gears are concerned, the grinding process may involve local overheating leading to heavy damages called grinding burns. In case carburized pinions, structure is typically made of martensite and bainite. The main structure of the carburized layer is martensite, and is very sensitive to quick heating and cooling. With such a phenomenon generated by the grinding wheel, it may appear cracked should the grinding wheel be worn or should a lack of lubrication arise (Fig. 28).

One method to check grinding burns is given in ANSI/AGMA 2007—C00. This method has demonstrated the first disadvantage to using hazardous products, such as nitric acid and alcohol, even if water can be used as an alternative to alcohol. The second disadvantage is that the procedure must be carefully followed to

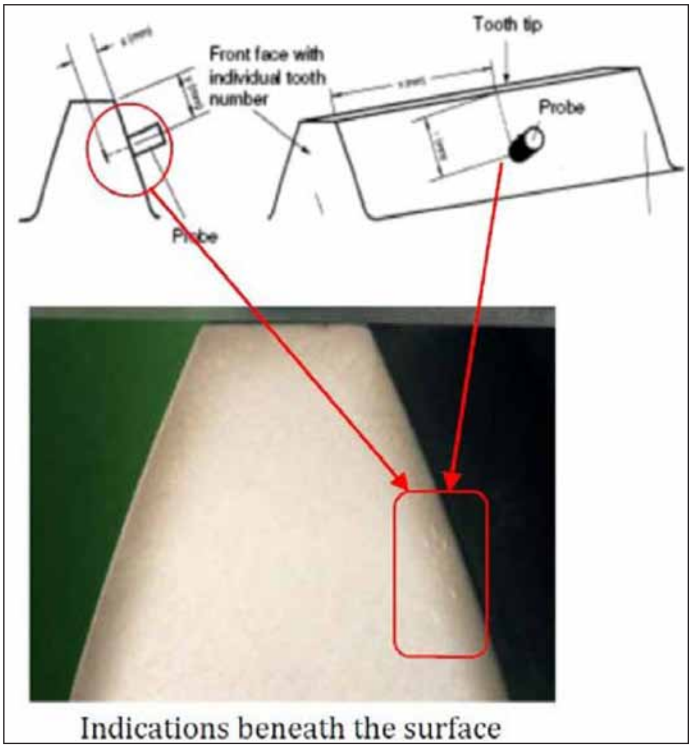


Figure 24—UT inspection procedure for inspection of subsurface defects.

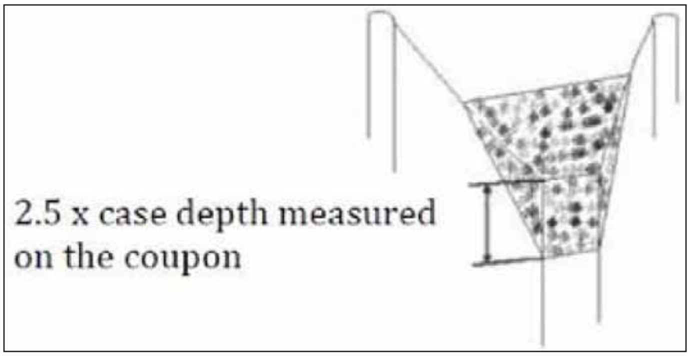


Figure 25—Sampling on an actual gear tooth for case-hardened layer inspection.

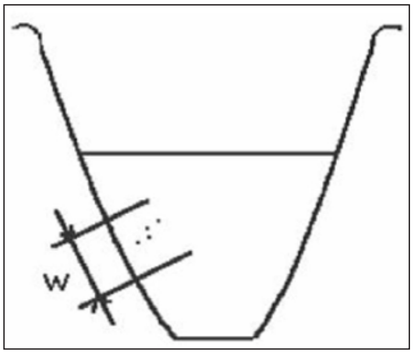


Figure 26—Case depth procedure of measurement on a sampling taken from a tooth.

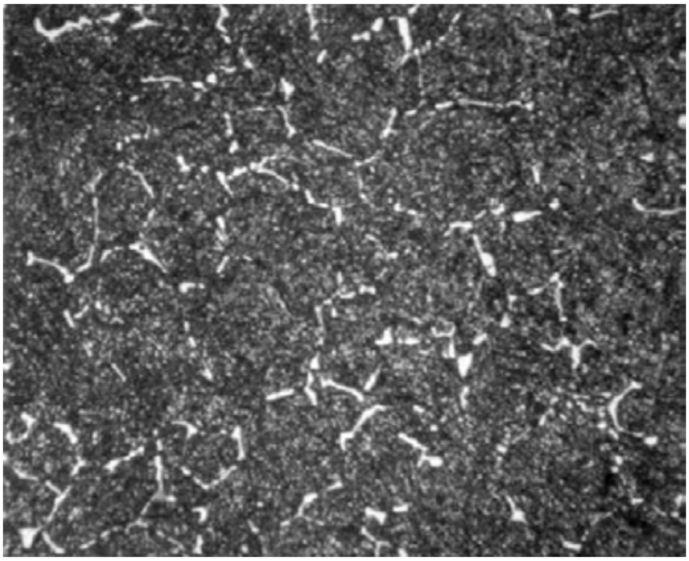


Figure 27—Case-carburized layer with carbide network.

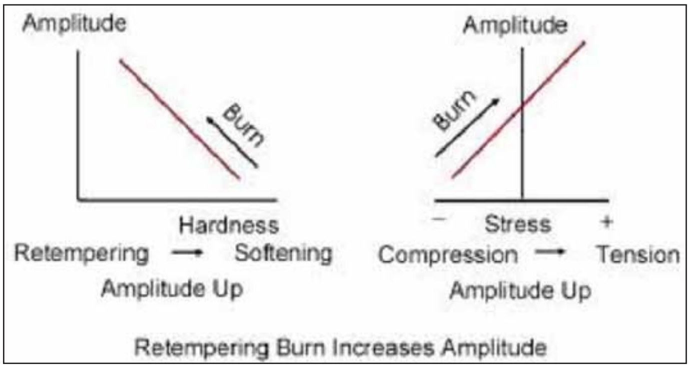
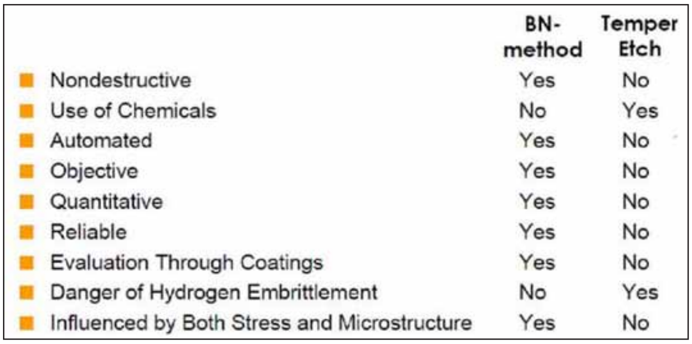


Figure 28—Grinding damage: re-tempering grinding burn.



	BN-method	Temper Etch
Nondestructive	Yes	No
Use of Chemicals	No	Yes
Automated	Yes	No
Objective	Yes	No
Quantitative	Yes	No
Reliable	Yes	No
Evaluation Through Coatings	Yes	No
Danger of Hydrogen Embrittlement	No	Yes
Influenced by Both Stress and Microstructure	Yes	No

Figure 29—Barkhausen noise vs. nital etching.

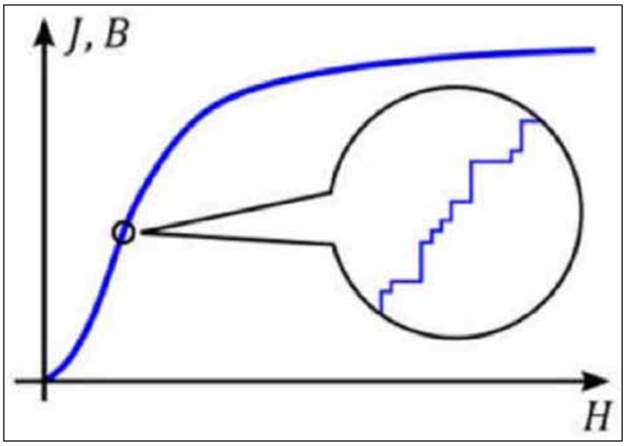


Figure 30—Effect of applied magnetic field in ferromagnetic material magnetic field changes—hysteresis.

avoid hydrogen embrittlement. The third disadvantage is the subjective interpretation of the "grey color." An alternative nondestructive method has been developed recently, Barkhausen noise inspection, BNA. Figure 29 is a comparison chart showing the advantages and disadvantages of the two methods.

Barkhausen was a German scientist who proved that magnetism not only affects atoms in a ferromagnetic material, but in fact the structural domains of it (called Weiss domains). In other words, a ferromagnetic material can be considered as an assembly of multiple magnets. Barkhausen also proved that magnetic changes in ferromagnetic materials are not continuous but tiny and steep, and related to discrete changes in size and orientation of each individual Weiss domain; the combination of all these changes gives magnetic hysteresis (Fig. 30).

When an alternative magnetic field is applied to the ferromagnetic material, these domains are forced to be reorganized in a direction relative to the applied magnetic field and their primary orientation. The constant reorganization generated by the alternative magnetic field induces a current. This is the so called Barkhausen noise. The induced current is then measurable, and typical of a specific material. The Barkhausen noise is dependent on several parameters, among which surface defects, residual stress, dislocations and hardness all play a role (at different levels). The higher the hardness, the lower the Barkhausen noise.

When applied to NDT, the Barkhausen effect allows detection of surface or near surface defects by the measurement of magnetic field perturbations. This measurement can either be acoustic or inductive (Fig. 31).

Over the past 15 years, this method has been successfully adapted to the search of overheated areas and grinding burns on ground pinions. Since it is comparatively a nondestructive test, calibration is the most difficult point. Barkhausen noise is dependent on chemical composition, hardness, dislocations, and residual stress. Of course, no calibrated samples are available for such large part application. In order to develop a dedicated process for such large case carburized pinion, a "library" of test samples of smaller size has been created. These samples are all made of the same material (18CrNiMo 7—6 according to EN 10084) and their sizes and carburized layer depth have been recorded to extract their influence from the Barkausen noise equation.

Meshing. Once the gear and pinion have been manufactured and inspected, now comes the moment to check how they work together. The mesh test is probably the easiest way to do so, but result interpretation is not as easy as one would think. This test can be carried out in three manners:

1. On the gear cutting machine, GCM;
2. Pinion on the ground, gear rolling over;
3. Gear on the ground, pinion rolling over.

The choice of test type is related to safety conditions, keeping in mind that the safer test is on the GCM. Results obtained through the three different methods are relatively equivalent, but testing on the GCM allows backlash adjustment, just like on site. However, it should be remembered that the mesh tests are done with no load, as opposed to what is done on site. This means shop mesh test and site mesh test can present some differences in terms of contact.

One of the key points is blue application. Contact of the gearing set obtained from the mesh test will mainly depend on blue thickness (or in other words, the capacity of the blue to fulfill gaps into the mating surface), and a little bit of the applied pressure (which is nothing compared to the load in service). Figure 32 illustrates the influence of blue thickness (same gear, same pinion for the 3 pair of prints):

As it can be seen, a very thin line of contact is legible when 5 mm of blue have been applied, a larger surface of contact is obtained with 10 mm (100% contact on the face width and 20% over the active profile), and 20 mm of blue gives a perfect contact (100% over face width and profile). What is also shown in Figure 32 is that 20 mm of blue were sufficient to fill the gaps between the gear tooth surface and the pinion tooth surface. In this case, lead tolerance of the gear and the pinion is 80 mm. This could lead to gaps between the two mating surface up to 160 mm, and will not authorize blue transfer. The roll test will then fail even though the gear and pinion are within tolerances. Summarily, the shop contact test is the most conservative test a gear set can undergo. If it passes the test, the gear set will work perfectly for years (at the ultimate condition, and assuming that site set-up is done correctly; but this is another story).

A correct interpretation of shop contacts can tell a lot about the way the gear and pinion have been cut, and if the gear cutting machine is reliable and functional. Years of tests have led us to write a guide of contact interpretation. The knowledge obtained from that study has been turned into machine and method improvements with the final goal to obtain the best meshing possible for the gear set. This parameter is so important today with the increase of mill power that these tests are conducted on every gear set.

Conclusion

Since mining mills become much more powerful, the pinion has to transmit more and more power through a single mesh and naturally becomes bigger and bigger. Whatever the size is, acceptance criteria remains unchanged. For such heavy parts, this means that the requirements are more stringent and imply the use of unconventional methods to meet with them. There is no longer a single part which is manufactured and inspected with a "rough" process. Related to the size increase, this article tries to show parameters to focus on and propose some acceptance criteria for both rough material as well as machining. These new criteria imply a "pull-up" of machine and inspection technologies to get more and more "high-tech" products capable of transmitting more power in a conventional manner (gear and pinion). The future is promising a lot in regards to these topics.

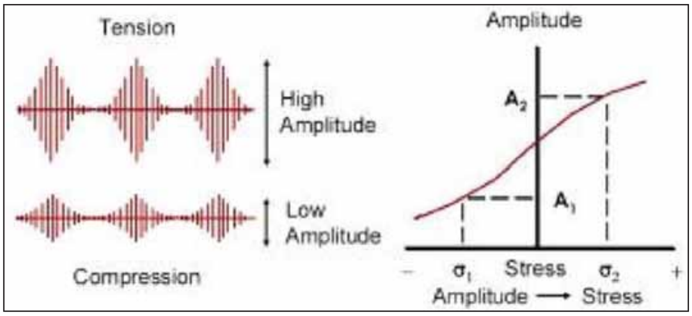


Figure 31—Effect of stress.

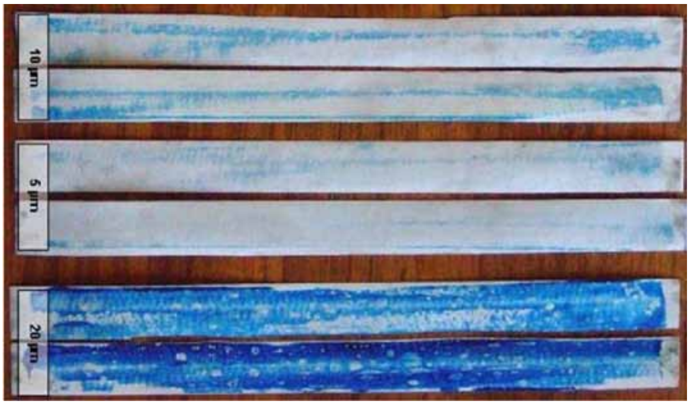


Figure 32—Influence of blue thickness on contact pattern record.

References

1. AGMA 218.01. "Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth."
2. ANSI/AGMA 2001—D04. "Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth."
3. AGMA 2000—A88. *Gear Classification and Inspection Handbook.*
4. ANSI/AGMA 6014—A06. *Gear Power Rating for Cylindrical Shell and Trunnion-Supported Equipment.*
5. Drago, R.J. and R.J. Cunningham. "*Hydrogen and Internal Residual Stress Gear Failures—Some Failure Analysis and Case Study,*" FTM 08FTM13.
6. "Tooth Interior Fatigue Fracture (TIFF)," Presented by the U.K. Delegation at the November 4, 2011 Plenary Meeting of ISO TC60 (ISO TC60/N1043).
7. Appolaire, B. "Prise en Compte Dumouvement des Cristaux Equiaxes dans Lamodélisation de la Solidification des Lingots d'Acier Coulés en Fonderie," Thèse INPL, 1999.
8. Appolaire, B. and H. Colombeau. "Modélisation de la Formation Demacroségrégations et Desmicrostructures Induites par la Sédimentation de Cristaux Équiaxes Pendant la Solidification de Gros Lingots d'Acier," Communication au Congrès Matériaux, Tours, 2002.
9. Jaouen O. "Modélisation Tridimensionnelle par Eléments finis pour l'Analyse Thermo Mécanique du Refroidissement des Pièces Coulées," Thèse de l'Ecole Supérieure des Mines de Paris, 1998.
10. Vannier I. *Modélisation de la solidification des ingots d'Acier,* Thèse NPL, 1995.
11. Wavelet, F. Roll "Test Result Interpretation, Ferry Capitain."
12. Pokorny A. and J. Pokorny. *Inclusion Non Métalliques dans les Aciers*, TI M220, 20 AGMA 12FTM14.
13. Bosson, J.C. Analyse de L'hydrogène dans les Aciers, TI M262.
14. Meyer, A., FILENGRENE, une Solution pour le Fraisage des Engrenages, JTM—INSA Lyon, 2011.
15. Stresstech. "Barkhausen Noise Analysis," Tool for Quality Control.
16. Olympus. "Phased Array Testing—Basic Theory for Industrial Applications," NDT field guide.

Michel Pasquier began his career in gearing upon graduation from the Ecole Supérieure de l'Energie et des Matériaux d'Orléans. In 1990 he took work in the automotive industry, focusing on automatic gearboxes for heavy vehicles and special differentials based on planetary gears. He joined CETIM in 1991, where until 2002 he resolved gear unit failures and worked with mechanical-related industries in the design of mechanical power transmissions. He moved to CMD Engrenages et Réducteurs in 2002 (to present) as technical support manager. Pasquier has served on the French delegation for ISO TC 60 (gears) and is a member of AGMA Committee 7e (6014).

Fabrice Wavelet is a metallurgist engineer who has since 1996 worked at Ferry Capitain, a CIF company, and as project manager/quality control since 2000. In 2003 he was charged with the technical supervision of production of all Ferry Capitain mining parts, which he also does for other CIF sister companies. Wavelet also lends technical expertise to other areas of the company, including R&D projects, non-destructive testing, material development and specification writing. In 2010 Wavelet and co-author Pasquier served on Committee 7e for revision of AGMA–6014.