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Technical Resources

12FTM14

AGMA Technical Paper

Large Pinions for Open Gears: The Increase of Single Mesh Load – A New Challenge for Manufacturing and Quality Inspection

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[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

Abstract

Most of the large open gear sets for mining industry are designed according to ANSI/AGMA 6014-A06 and ANSI/AGMA 2001-D04.

Basically, customer specifications and AGMA service factor ratings both depend on design of the pinion (including material selection and heat treatment), as well as the finishing process of the teeth (to achieve the designed geometry).

Today, with the increase of mesh load, design and manufacture of gearing to meet specifications and ratings becomes even more challenging.

In complement to the traditional mechanical properties (such as hardness or yield strength), elastic and thermal behaviors and their influence on transmission accuracy have to be taken into account from the design stage, especially for large open gears (over 5 m in diameter).

That implies a rise of cutting quality selected at the design stage, and of course and consequently, improvements in manufacturing and quality control, as normal processes that were used successfully for years are nowadays reaching their limits.

This paper, using detailed examples, introduces these mandatory improvements in design, manufacturing and inspections, starting from material elaboration to final machining, and focus on today's large and powerful gearing.

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1001 N. Fairfax Street, Suite 500
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October 2012

ISBN: 978-1-61481-045-2

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Introduction

This paper is based on the fact that mining mills are becoming more and more powerful (up to 8500 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. The methods that have been used successfully for years must improve. Most customers have already taken into account this situation, in the requirements of their technical specifications.

Starting from the 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, defined by the worldwide agreed standard ANSI/AGMA 6014-A06.

Gear rating according 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 as well as for 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} :

$$P_{acm} = \frac{\pi n_p F}{396\,000} \frac{I}{K_{vm} K_m} \left(\frac{d s_{ac} Z_N C_H}{C_p} \right)^2 \quad (1)$$

$$P_{atm} = \frac{\pi n_p d}{396\,000} \frac{F}{K_{vm} P_d} \frac{J s_{at} Y_N}{K_m K_{Bm}} \quad (3)$$

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 depending on material.

Their definition and actual results condition the service life, no less. In other words, the control of the manufacturing and inspection of the parameters that make these criteria, is of the most importance.

Material

Material is of great importance to the 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 7000 kW (9387 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 all through the part is a challenge. A perfect control of the manufacturing process and quality control from the ingot casting to the final heat treated forging (including case hardening) is mandatory. That's what the selection of a M2 material is bringing.

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.) as well as some 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:

- **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, 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 local over-concentration of alloying elements, implying a fall of mechanical and fatigue properties and 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. An example of computer simulation and comparison with the actual ingot is given in Figure 1 and Figure 2.

Cleanliness

Cleanliness is on the top of metallurgical standard requirements for obvious reasons. 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. In ANSI/AGMA 6014-A06, the cleanliness requirement is according to ASTM 866 or AMS 2301. ISO 6336 refers to ISO 4967. Sometimes, steel manufacturers rate cleanliness in accordance with DIN 50 602, method K. Should we consider only ANSI/AGMA 6014-A06 cleanliness requirements for steel pinions which are meant for the teeth area (table 5, note 2), while case carburized pinions have different requirements (table 7, item 4).

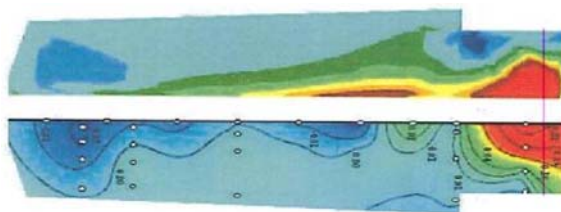


Figure 1. Computer simulation of segregation

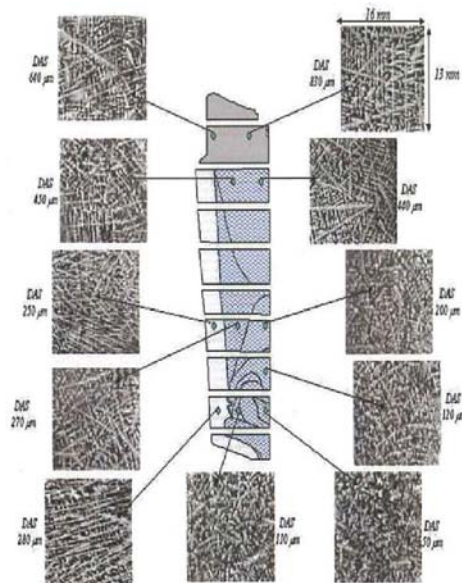


Figure 2. Actual segregation in ingot

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, alumina's, 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 been made evident for many years 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 in an exponential rate. Combined with inherent material dislocations and atomic diffusion (embrittlement is a very complicated process), hydrogen may lead to severe damages. A well know effect of that, and probably the most typical, is a sudden break while efforts undergone by the part are very low. See Figure 3 and Figure 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.



Figure 3. Sudden breakage due to hydrogen embrittlement



Figure 4. Magnification of hydrogen burst in the broken surface

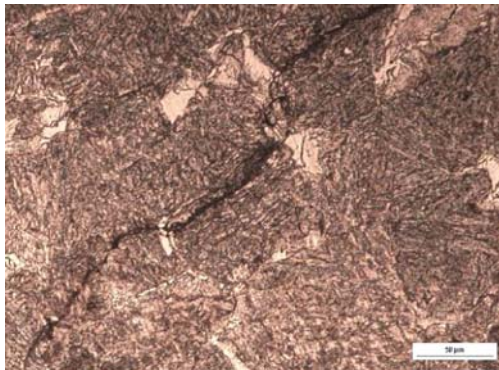


Figure 5. Free hydrogen influence - microcrack formed during forging

The origin can be summarized as follows:

Steel Ingot → Dendrites → Segregations + Free H_2 → Embrittlement → Cracking

A solution to avoid such embrittlement is to maintain a low level of free hydrogen. This can be achieved by requiring vacuum de-gas 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 amount. 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, as shown in Figure 6.

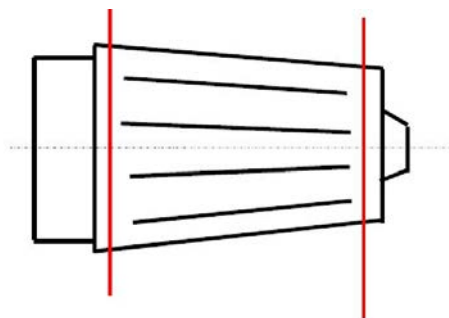


Figure 6. Ingot location of head and foot cuts