

Non-metallic Inclusion and Their Effect on Fatigue Strength for Case-Hardened Carbon Steel in Gears

Izudin Dugic, Robin Berndt, Simon Josefsson and Martin Hedström

Abstract Steel is a very essential structural material and its production worldwide has shown significant increase over the last years. In steels there always exist a large number of inclusions which can have a degrading effect on the fatigue properties. This study is focused on the link between the characteristics of non-metallic inclusions and how they affect fatigue strength of the standardized case-hardened carbon steel 20MnCr5 and a version of this steel with a more favorable inclusion distribution, a so-called Clean steel. For the evaluation of the mechanical properties the test result from rotary bending tests are compared and an improvement by 37.5% in fatigue strength can be noted between the different steels. The new performed ultrasonic tests illustrate the difference in the size of defects in materials with different manufacturing processes and degree of reduction. By studying international and European standards for non-destructive testing and investigation of alloy compounds, the current material specification can be adjusted.

Keywords Steel • Clean-steel • Inclusions • Mechanical properties
Ultrasonic test • Standard

Introduction

The cleanliness in a steel is of great importance for the strength in general and the fatigue strength in particular. Non-metallic inclusion is a recurring problem in the production and casting of steel. Variation from specification in respect to inclusion distribution inevitable leads to costly reparations, downgrading or recycling of large quantities of material. There are different types of inclusions present in steel which

I. Dugic (✉) · R. Berndt · S. Josefsson
Faculty of Technology, Department of Mechanical Engineering, Linnaeus University, Växjö,
Sweden
e-mail: Izudin.dugic@lnu.se

M. Hedström
China Euro Vehicle Technology AB, Göteborg, Sweden

depends strongly on the production route, alloy composition and technical conditions of the process [1, 2].

The influence on the mechanical properties of inclusions is decided by the size, thermal expansion coefficient, modulus of elasticity and the deformability of said defects. A greater inclusion size in general leads to lowered mechanical properties. If the thermal expansion coefficient is greater than that of the metal, it will shrink more in the solidifying process leading to compressive residual stresses around said defect. If on the other hand the thermal expansion coefficient is lower than that of the metal, it will shrink less in the solidifying process, leading to tensile residual stress around the defect [2].

When it comes to dynamic loaded parts such as engines, gears, shafts and turbines the most occurring cause of failure today is material fatigue due to the many load cycles associated with parts such as there [3].

The purpose of fatigue tests with cycles between 10^6 and 10^7 is to statistically map the mean value and spread of the fatigue limit. There are different models developed and available for gathering data and calculation of the fatigue limit where the most common is the staircase-method, also known as the up and down method [4–8].

The data collected with the staircase method can through the “Dizon-Mood”-equations be used to calculate a mean value, $\hat{\mu}$ (Eq. 1) and a standard deviation, $\hat{\sigma}$ (Eq. 2) for the fatigue limit (S_n) [4–8].

$$\hat{\mu} = S_0 + s \times (B/A \pm 0.5) \text{ [MPa]} \quad (1)$$

$$\hat{\sigma} = 1.62 \times s \times (A \times C - B^2/A^2 + 0.029) \text{ [MPa]} \quad (2)$$

With the results from Eqs. (1–2), a 99.9% confidence limit is calculated:

$$\hat{\mu} - 3.291 \times \hat{\sigma} \sqrt{N} = 99.9\% \text{ confidence limit} \quad (3)$$

Currently, there exist two general methods for computation of the allowed fatigue stress for gears in accordance with ISO 6336 called method A and method. The method which is used for computation of the nominal stress value with respect to bending ($\sigma_{F\text{lim}}$) and contact fatigue for gears ($\sigma_{H\text{lim}}$) is the method B. Method B is comprised of different ways to compute and estimate the maximum bending and contact stress at the gear root and tooth flank of said gear [9].

For calculation of the nominal stress value for bending, the following steps can be used. The value for the confidence limit is used as the allowable stress number (σ_{FE}). The nominal stress value can consequently be calculated with the Eq. (4). The stress correction factor (Y_{ST}) needs to be decided and used. A reference gear in according to ISO 6336 should be manufactured with a value of 2.0.

$$\sigma_{F\text{lim}} = \sigma_{FE} / Y_{ST} \text{ [MPa]} \quad (4)$$

Standardized values for the allowed nominal stress value for bending and contact fatigue can further be calculated with the use of Eq. (5) where the factors A and B can be found in the standard. The value of x is the surface hardness, which based on the type of material has a specified maximum value used for calculation [9].

$$\begin{cases} \sigma_{H\ lim} \\ \sigma_{F\ lim} \end{cases} = A \times x + B \text{ [MPa]} \tag{5}$$

Experimental

Materials

The Company produces several different components to the automotive industry. The European standard EN 10084 (DIN reference number 1.7149) has the status of the Company standard for Steel 20MnCrS5 used for construction of gears. The Company has some additional requirements regarding the chemical composition as shown in Table 1 [10].

The extent of micro inclusions (oxides) in the steel is referred to DIN 50602-1985, method K. Materials with a diameter less than 50 mm should be rated to K4 with a maximum allowed score of at most 30 and materials with a diameter above 50 mm must also be rated with K4 with a total score of at most 40. The K value defines the minimum size in width and length of inclusions used for purity evaluation. The value defined after K4 (40/30) is based on a scoring system where a major defect gets a higher factor. Number of defects multiplied by factor for individual defect forms a score. The total score is converted to an average for a certain area [11].

For the in line ultrasound inspection the acceptance criteria shall be in accordance to EN 10308, Table 2 as follows:

- diameter ≤ 100 mm: quality class 4,
- diameter > 100 mm: quality class 3 [12].

In order to investigate the size of non-metallic inclusions in the steel, a series of ultrasonic testing were made on the standardized case-hardened carbon steel

Table 1 Chemical composition of 20MnCrS5 steel

Chemical composition in % (mass fraction)										
C	Si max	Mn	P max	S	Cr	Mo max	Ni max	Al	Cu max	N
0.16– 0.22	0.025	1.10– 1.35	0.025	0.020– 0.035	1.00– 1.30	0.08	0.25	0.015– 0.050	0.25	0.080– 0.014

Table 2 Chemical compositions of the evaluated steels

Steel	Chemical composition in % (mass fraction)								
	C	Si	Mn	P	S	Cr	Mo	Ni	Al
A	0.16–0.22	max 0.25	1.10–1.35	max 0.025	0.020– 0.035	1.00–1.30	max 0.08	max 0.25	0.015– 0.050
B	0.17–0.22	max 0.40	1.10–1.40	max 0.025	max 0.035	1.00–1.30	–	–	–
C	0.17–0.22	max 0.40	1.10–1.40	max 0.025	max 0.035	1.00–1.30	–	–	–
D	0.15–0.18	0.20– 0.35	0.50–0.60	max 0.015	0.008– 0.015	1.50–1.80	0.25– 0.35	1.50– 1.70	–
E	0.15–0.21	max 0.40	0.50–0.90	max 0.025	max 0.035	1.50–1.80	0.25– 0.35	1.40– 1.70	–
F	0.17–0.22	0.20– 0.35	1.10–1.40	max 0.025	0.015– 0.025	1.10–1.30	max 0.08	max 0.025	0.020– 0.040

20MnCrS5 manufactured with continuous casting (in this work called Steel A) and the results are compared with earlier ultrasonic testing of 20MnCr5 manufactured with ingot casting (in this work called Steel B) and on the cleaner variant of 20MnCr5 manufactured with ingot casting (in this worked called Steel C). The chemical compositions of the evaluated steels are shown in Table 2.

For the evaluation of the mechanical properties the data on previously performed tests from rotary bending testing are compared. The materials evaluated are Steel 18CrNiMo7-6 manufactured with continuous casting (in this work called Steel D), Steel 18CrNiMo7-6 manufactured with ingot casting (in this work called Steel E) and Steel 20MnCr5 manufactured with ingot casting (in this work called Steel F). The chemical compositions of the evaluated steels are shown in Table 2.

Ultrasonic Testing

The machine which conducted the ultrasonic testing was an USIP 20, manufactured by Krautkramer Branson, equipped with a 10 MHz probe, calibrated to a FBH of 0.2 mm. The machine is calibrated using a reference peace of steel with a height of 60 mm and a diameter of 30 mm where a hole with the diameter 0.2 mm has been drilled to a depth of 1 mm. The reference steel is further scanned and the drilled hole acts as a reference for the size of defects that the machine is designed to find and indicate.

The conducted tests of steel A is made through preparing 5 cylindrical samples with a length of 250 mm and diameter of 80 mm. The material is delivered in soft annealed condition but gets normalized through annealing in 920 °C for 1 h after which it cools off before processing. The normalization process is carried out to minimize acoustic abnormalities before the ultrasonic testing. The material is milled



Fig. 1 Scanning of test material

10 mm on two opposite sides to achieve correct thickness of 60 mm and a plane surface for testing. The material is placed in a water tank and the 10 MHz probe scans the 5 samples, see Fig. 1. A graphical image is presented showing the size and distribution of detected inclusions present in the samples.

The data gathered from previously conducted tests are compiled and analyzed. The data consists of protocols from 5 samples of steel B and 2 samples from steel C.

Mechanical Testing

The data presented is the result of fully reversed rotational bending fatigue testing conducted with an Amsler UBM 200. All tests are conducted with specimens designed with a great radius to minimize the influences of stress concentrations. The tests are furthermore conducted and analyzed using a staircase method with stress levels varying with 25 (MPa). All samples are prepared from the transverse

direction, in through hardened condition with a smoothness of maximum 0.3 Ra. Each specimen is measured on the thinnest section and the load is modified to ensure a precise value for the effective stress the specimen is subjected to.

From the conducted tests 9 values for steel D, 5 values for steel E and 11 values for steel F can be used for calculation of the nominal stress value.

Results and Discussion

Ultrasonic Testing

The results from ultrasonic testing are shown in Table 3.

Mean value of defects in the weight of 10 kg for Steel A is 109.5 and the mean value for number of defects > 0.2 mm FBH/dm³ is 9.6. These results for Steel A are shown as graphical images in Fig. 2.

Tests results for the five test specimens of Steel A shows 14 defects which are equal to or greater than the reference hole, 15 defects are in the range 50–99% of the reference hole, 17 defects in the range 30–49%, and 8 defects between 25 and 29% of the reference hole. In total a number of 54 defects are noticeable which corresponds to 25% or greater than the reference hole. The defects appear as white dots in the blue fields for each test piece. The results for Steel B and C show no noticeable defects which are greater than 25% of the reference hole.

After examining and evaluation of the ultrasonic tests, a clear difference in size and frequency of defects associated with the two process routes between the materials can be clearly distinguished.

Table 3 Results from ultrasonic tests

	Weight kg	25–29%	30–49%	50– 99%	≥	Weighted value for each 10 kg	Number of defects > 0.2 mm FBH/dm ³
Steel A	2.27	2	1	5	3	125.6	10.3
	2.36	0	4	0	0	16.9	0
	2.24	3	9	4	9	285.7	31.3
	2.29	0	1	0	0	4.4	0
	2.35	3	2	6	2	114.9	6.6
Steel B	1.7	0	0	0	0	0	0
	1.88	0	0	0	0	0	0
	1.77	0	0	0	0	0	0
	1.84	0	0	0	0	0	0
	1.84	0	0	0	0	0	0
Steel C	2.88	0	0	0	0	0	0
	2.90	0	0	0	0	0	0

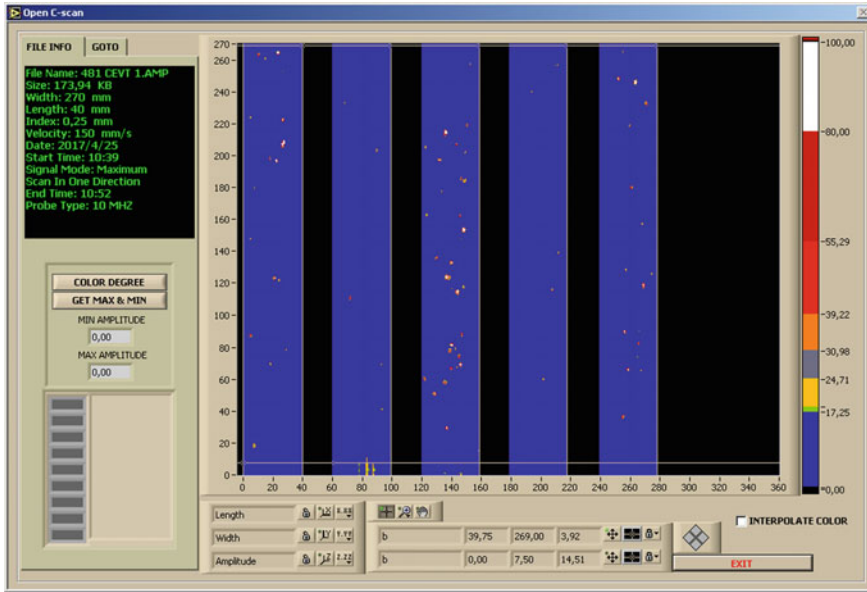


Fig. 2 Results from the ultrasonic test for steel A

The tests performed and evaluated cohere with the theory of what a 10 MHz probe can detect when only defects down to the size of 120 μm could be notated. When increasing the frequency up to 25 MHz, the effective thickness of material being tested is reduced from 60 to 25 mm as the size of defects that can be found is reduced to 50–100 μm. The possibility of removing slag in the bottom of the ladle by unloading some of the melted steel prior to casting and the possibility of a higher degree of reduction of a steel has an effect on how large inclusions a steel possesses proved to be true in the examination of the ultrasonic tests. A steel which is continuous casted are less likely to achieve as high reduction degree as an ingot casted steel and thus generally consist of an increased size of inclusions.

Mechanical Testing

Results of the calculations using Eqs. (1–3) on all materials which have been tested for bending fatigue can be seen in Table 4.

From the performed test, nine values could be used to calculate a nominal stress value for Steel D, see Fig. 3.

From the performed test, five values could be used to calculate a nominal stress value for Steel E, see Fig. 4.

From the performed test 11 values could be used to calculate a nominal stress value for Steel F, see Fig. 5.

Table 4 Results from bending fatigue

Material	$\hat{\mu}$ [MPa]	$\hat{\sigma}$ [MPa]	Confidence limit (99.9%) [MPa]
Steel D	537.5	21.4	502.3
Steel E	779.2	41.7	690.5
Steel F	922.5	75.7	810.6

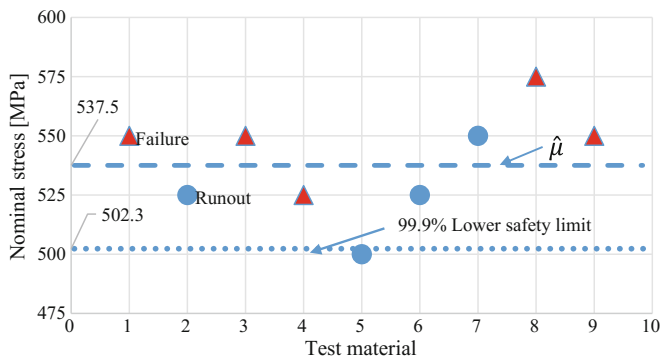


Fig. 3 Rotating bending test on Steel D

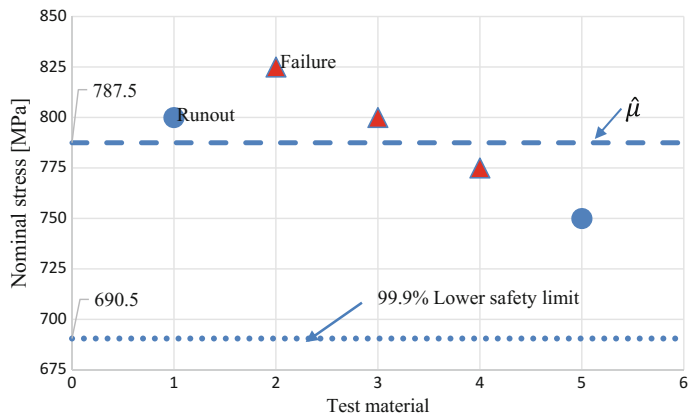


Fig. 4 Rotating bending test on Steel E

By using Eq. (4), nominal stress value for gears is calculated for the materials which the rotating bending test have been performed on. The result can be seen in Table 5.

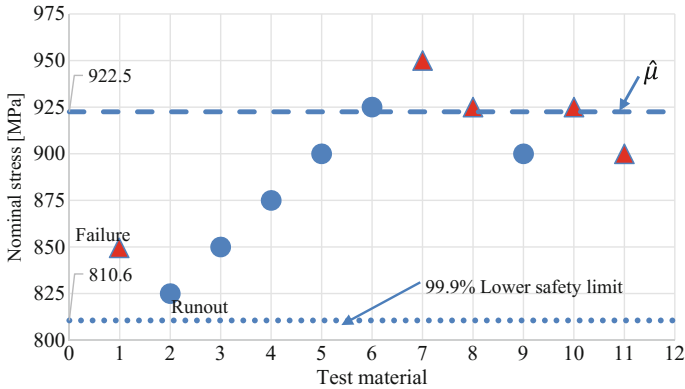


Fig. 5 Rotating bending test on Steel F

Table 5 Results of nominal stress values for bending fatigue

Material	Lower safety limit (99.9%) [MPa]	Nominal stress value for bending fatigue for gears ($\sigma_{F\ lim}$) [MPa]	Difference in stress value [%]
Steel D	502.3	251.2	0
Steel E	690.5	345.3	+37.5
Steel F	810.6	405.3	+61.4

Table 6 Results of comparison for 20MnCr5 steel

Material	Nominal stress value for bending fatigue for gear ($\sigma_{F\ lim}$) [MPa]	Difference in stress value [%]
Through hardened wrought steel (MQ)	340.0	0
Through hardened wrought steel (ME)	370.6	+9
Stell F	405.3	+19.2

By using Eq. (5) a comparison of the nominal stress value can be made between the steel 20MnCr5-IC and that from the standards for through hardened carbon steel in the classes ME and MQ [9]. The results can be seen in Table 6.

Conclusions

There is a clear difference in the distribution of defects between the two process routes continuous casting and ingot casting. Steel manufactured with ingot casting shows a significantly higher purity when performing ultrasound tests with a

10 MHz probe compared to that of a material manufactured with continuous casting.

The result shows a clear improvement in fatigue strength as the distribution of defects becomes more beneficial.

An improvement of fatigue strength for applications connected to power transmission can be proved by comparing results on rotating bending tests of the 18CrNiMo7-6 material in continuous casting versus ingot casting. To get an exact value which can be used in real applications e.g. strength calculations of gears a more applied test procedure such as a FZG-test or pulsator-test is recommended. This because of the uncertainty that occurs when transferring test data for bending stress between general fatigue strength and the value used to calculate fatigue strength of gears ($\sigma_{F\ lim}$).

To monitor the size and distribution of defects and ensure that steel with higher purity meets the requirements specified in the material specification, a lower K-value and score should be implemented when performing tests in accordance with DIN 50602. It should also be added that there are other standards for mapping and evaluating inclusions such as ASTM E45 and ISO 4967. To get a material specification that clearly describes and processes the defects in a material, an implementation of these, individually or in combination with each other, may be considered.

When verifying the distribution of defects with an ultrasonic test, a smaller FBH is recommended for calibration. Due to the decreased volume tested, per unit of time, when increasing the frequency for detection of smaller size defects, no increase in frequency is recommended at an initial stage. The fatigue strength which can be achieved with these implementations are based on the size of defects that can be found with a 10 MHz probe.

Acknowledgements The author would like to thank Linnaeus University, Faculty of Technology, Department of Mechanical Engineering, Växjö, Sweden and China Euro Vehicle Technology AB, Göteborg, Sweden.

References

1. Zhang L, Rietow B (2006) Large inclusions in plain-carbon steel ingots cast by bottom teeming. http://www.jstage.jst.go.jp/article/isijinternational/46/5/46_5_670/_article.pdf. Accessed 9 Apr 2017
2. Andrew B (2012) The effect of microstructure and induction processing on fatigue performance and crack initiation of induction hardened bar steel. <http://dspace.library.colostate.edu/handle/11124/76674>. Accessed 23 Mar 2017
3. Kamjou L, Hansson H (2015) Innovative steel design and gear machining of advanced engineering steel. AGMA technical paper
4. Lee Y, Pan J, Hathaway R (2004) Fatigue testing and analysis. Butterworth-Heinemann, USA
5. Pollak R (2005) Analysis of methods for determining high cycle fatigue strength of a material with investigation of Ti-6Al-4V gigacycle fatigue behavior. <http://www.dtic.mil/dtic/tr/fulltext/u2/a441887.pdf>. Accessed 23 Mar 2017

6. Nakazawa H, Kodama S (1987) Statistical S-N testing method with 14 specimens: JSME standard method for determination of S-N curves. In: Statistical research on fatigue and fracture
7. Dixon WJ, Mood AM (1948) A method for obtaining and analyzing sensitivity data. *J Am Stat Assoc* 43:109–126
8. Brian V, Ervin Z (2017) Rolling-element fatigue testing and data analysis—a tutorial. <http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20110008238.pdf>. Accessed 25 Apr 2017
9. International Organization of Standardization, ISO 6336:2006
10. EN 10084:2008-06: Case hardening steels—technical delivery conditions
11. DIN 50602-1985: Microscopic examination of special steels using standard diagrams to assess the content of non-metallic inclusions
12. European Standard EN 10308:2002: Non-destructive testing—ultrasonic testing of steel bars