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Qualitative comparison of PM gear impact performance, equipment, methodology and results

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Abstract

One of the modes in which a gear can fail is through sudden shock loads, caused by for instance abuse of the transmission. Therefore the question of how PM gears can take abuse loads compared to wrought materials often arises when looking at new application for sintered gears. In the paper the development of a new equipment to test impact strength of gears is described. It is also described how the staircase method, often used to determine for instance endurance limits in fatigue testing, can be employed to determine the impact strength of a gear. Finally results for different powder metal steels at different densities and heat treatments are presented, along with a comparison of a typical wrought steel.

Introduction

Gear are important machine elements in many applications, and are normally designed on criteria such as fatigue strength and wear resistance. But also other factors can play an important role in some applications, such as sudden loading or impact. This could for instance be the result of a bad gear change in a manual car, and often different abuse tests are included in the qualification of a new transmission. Therefor the question about gear impact strength often arises when investigating the possibility to use PM in a certain gear application, for instance an automotive gearbox.

Impact strength is often measured through the Charpy test, and other test methods can also be found for certain applications. But since no standardized test method for gear impact strength was found it was decided to develop a test procedure that can investigate how different materials and processing conditions influence the impact strength. The reason to do testing on gears rather than just compare data was to have a more application like setup taking factors such as stress distribution and residual stresses of the actual component into account.

In this paper both the design of a rig for gear impact testing as well as a methodology to evaluate the results are described. Results for different PM materials are also given along with a comparison to wrought steel. The methodology is also compared to standard Charpy tests.

Gear impact test rig

The basic principle of the test procedure used here for gear impact testing is a drop weight test. A certain weight is dropped from a certain height onto a gear tooth, resulting in the tooth breaking off or not. By varying the drop height it's possible to determine the energy required to fracture a gear tooth. Figure 1 shows a sketch with the different parts of the test rig along with a picture of the actual implementation. At the bottom the specimen holder is placed with a gear, see also Figure 2. A hammer is placed on rails so that when released, it will hit on the specimen holder. On the hammer different weights can be placed depending on the test, the weight of just the hammer is 1.39 kg. A height adjustment allows to adjust the drop height. Before the test the hammer with weights is held in place with an electromagnet that can be turned off to release the impact.

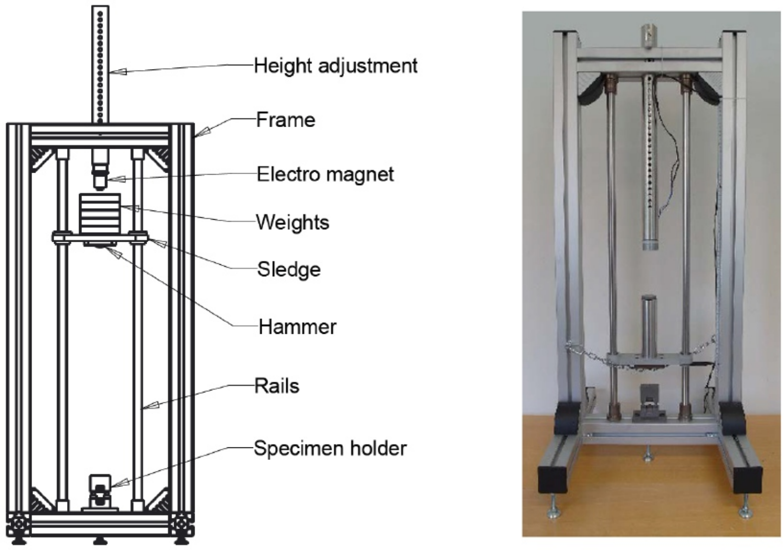

Figure 1. Sketch of the design of the test rig and photo of the actual implementation.

Figure 2. Sketch of gear specimen holder.

To analyse the data from the drop weight tests, it was decided to use the staircase method. This methodology is well known for instance from fatigue testing, but was developed for instance to test drop weight tests of explosives [1]. The basic idea is to select a weight, that is kept constant during the test, and then drop it from a certain height. If the gear sustains the drop the height is increased by a given step, and if it breaks decreased with the same pre-selected height step. The process is then repeated until sufficiently many data points have been gathered, after which the data is processed according to the methodology described in [1]. This way the average and standard deviation of the drop height, h_c, can be calculated and from that, along with the weight, m, used, the fracture energy calculated through:

$$GI = mg'h_c \tag{1}$$

with g' denoting gravitational acceleration compensated for friction and drag. By filming the drop test with a high frame rate it was possible to estimate the effective acceleration, g', for different hammer weights. An example of such a measurement is given in Figure 3, where it's seen that a higher weight yields a higher acceleration due to less relative influence of friction and drag. Several measurements were made and the average g' for different weights is given in Table 1. These are the values that are used to calculate the energy according to equation (1).

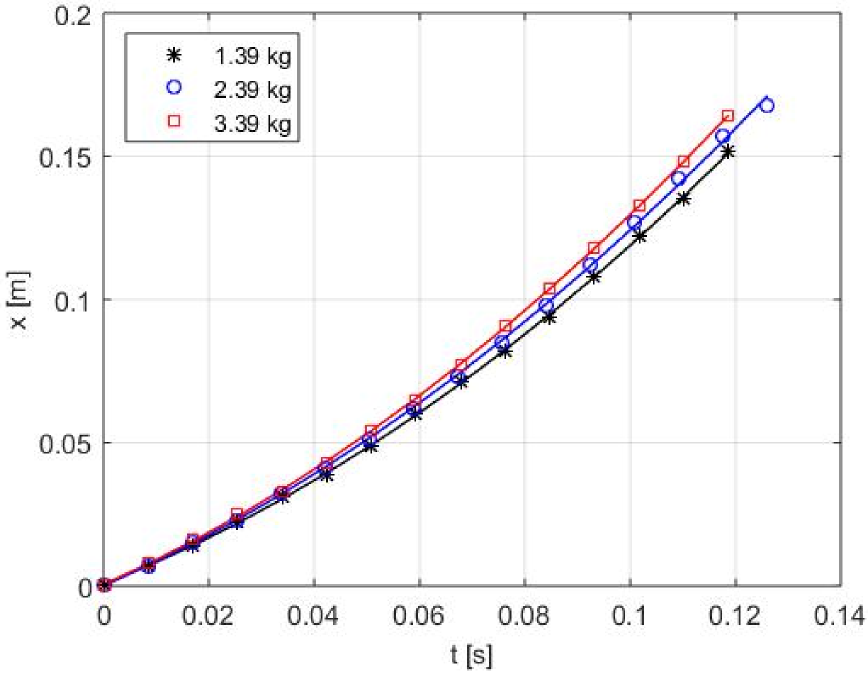

Figure 3. Acceleration measurements

Table 1. Measured acceleration as function of weight.

m [kg]	g' [m/s^2]
1.39	8.84
2.39	9.08
3.39	9.60

Experimental investigation

To investigate the equipment and the test method to generate impact test data on gears, a set of experiments were conducted. The gear geometry used for the experiments is given in Figure 4. This gear was selected since a compaction tool was available, the gear holder is also able to take other spur gear geometries. All gears were compacted, sintered, case hardened and tempered (at 200°C for 60 min in air), except the wrought steel reference that was hobbed, case hardened and tempered. No hard finishing was done to any of the gears. To investigate the influence of both composition and density gears of different materials and densities were tested. All sintering was done at 1120°C for 30 min in a 90/10 N_2/H_2 atmosphere, Table 2 shows an overview of the different variants.

Module: m_n=1.5875 mm
Numberof teeth: z=18
Pressure angle: α_n=20°
Profile shift: x=0
Tip diameter: d_a=31.75 mm
Root diameter: d_f=24.61 mm
Gear width: b=10 mm

Figure 4. Gears used for the experiments.

Table 2. Overview of materials

Material	**Density [g/cm^3]**	**Heat treatment**
Astaloy Mo (Fe-1.5%Mo)+ 0.2%C-UF4+0.6%LubeE	6.8, 7.0 and 7.2	Gas carburizing +tempering
Astaloy CrA (Fe-1.8%Cr)+0.2%C-UF4+0.6%LubeE	7.0 and 7.2	Low pressure carburizing + tempering
Distaloy AE (Fe/1.5%Cu/4%Ni/0.5%Mo)+0.2%C-UF4+0.6%LubeE	7.0 and 7.2	Gas carburizing + tempering
SS2506 (Swedish standard corresponding roughly to 20NiCrMoS2)	Full density	Gas carburizing + tempering

Due to problems with the case hardening the PM gears turned out more or less through hardened with a fully martensitic structures, in the case of Distaloy AE Ni-rich austenite was also present, without a clear case depth. Figure 5 shows examples of the micro structures for the different material.

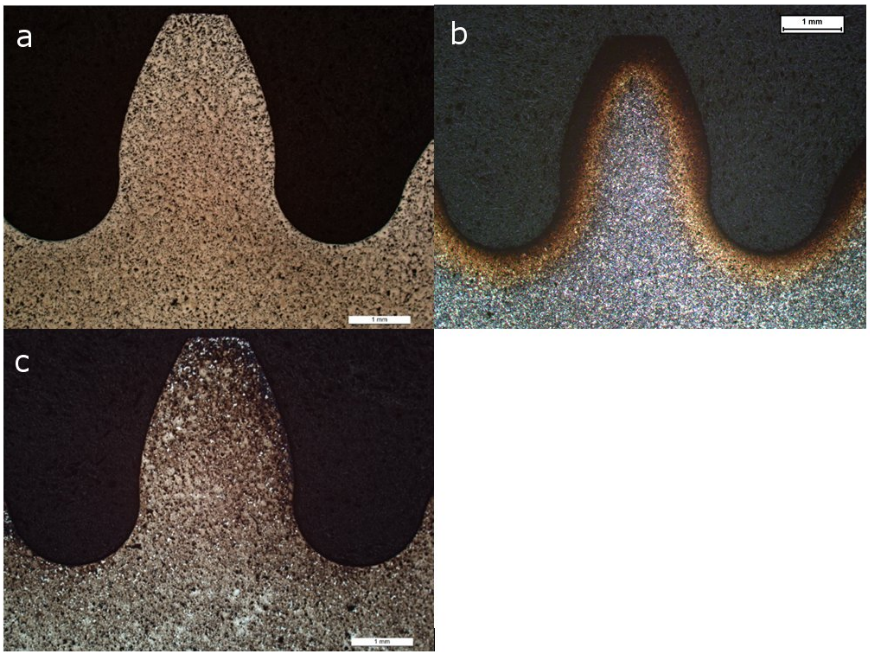

Figure 5. Microstructures, a. Astaloy Mo, b. Astaloy CrA and c. Distaloy AE.

Table 3. Summary of impact energy tests.

Material	**GI [J] [m=1.39 kg]**	**GI [J] [m=2.39 kg]**	**IE [J]**
AstMo 6.8	1.72	2.01	8.20
AstMo 7.0	2.27	2.93	9.75
AstMo 7.2	3.14	3.77	11.3
AstCrA 7.0	2.12	2.28	6.95
AstCrA 7.2	2.13	2.33	7.22
DistAE 7.0	2.77	3.17	12.1
Dist AE 7.2	3.62	4.14	15.9
SS2506	-	8.3	-

The gears were tested in the gear impact rig using drop weights of both 1.39 and 2.39 kg, standard Charpy testing was also done on the PM steels. Typically 15 tests were used in the staircase per series. The exception was SS2506 where only four points could be obtained since only one gears was available to test. Thus the uncertainty in this value is very high and is only included to give a rough comparison to PM steels. A summary of the results are given in Table 3 and Figure 6.

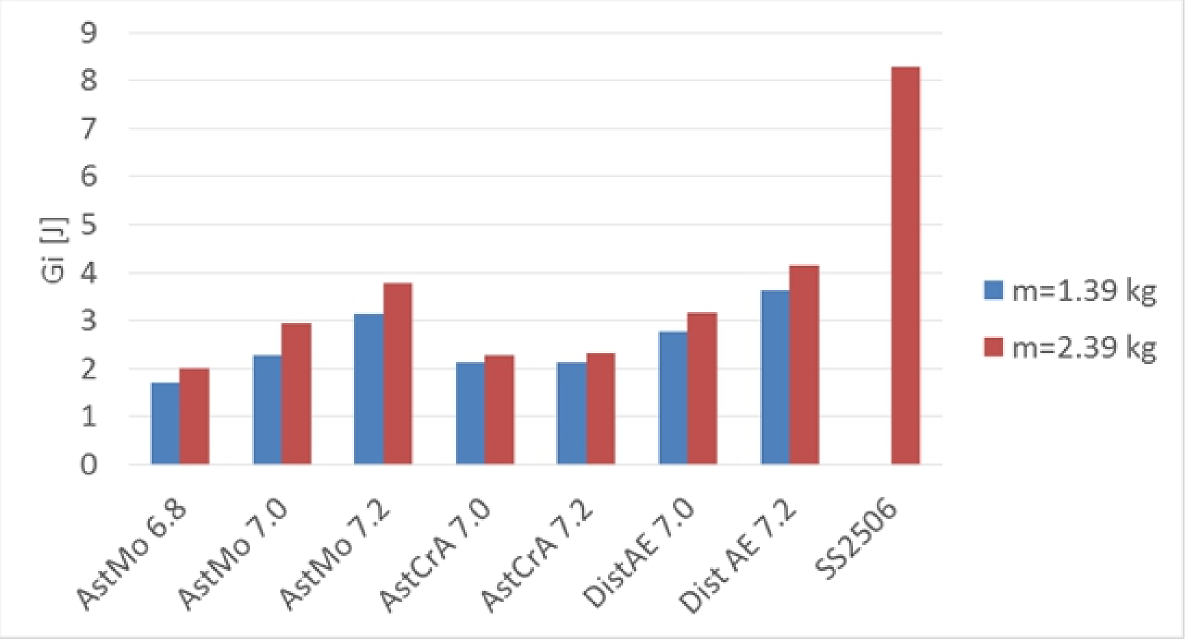

Figure 6. Summary of results from impact testing.

As can be seen from the results the impact energy increases with density, as expected. The exception is Astaloy CrA, which showed very little influence of density on the impact strength. It was also found that a higher impact mass in the test rig gives a higher fracture energy. This could be a result of the higher available energy at impact due to a higher weight giving a higher strain rate during the deformations, and that fracture toughness depends on strain rate [2].

Comparing the different materials shows slightly higher values for Distaloy AE compared to Astaloy Mo, probably due to the Ni content of the material. Astaloy CrA, in turn, showed lower impact strength. The wrought steel, SS2506, had around twice the gear impact strength compared to the higher density PM materials tested. This comparison should be verified with further testing, especially since only very few points were tested for the wrought steel.

It is also of interest to compare the gear impact energy with the results obtained from a standard Charpy test. Figure 7 shows Charpy IE versus GI, with a load of 2.39 kg. It's apparent that there is a correlation between the values, with a correlation coefficient of r=0.91. It can also be noted that normalizing the fracture energy with the total fracture area yields almost a one to one correlation for the data in Figure 7.

This means that in many cases the standardized Charpy test is probably sufficient to compare the impact strength of different materials. But there could be situations where it is advantageous to do the test on the actual component, with the proper heat treatment etc. Also the behavior of different gear geometries can be compared this way. For such cases the presented gear impact test method seems to be a good option.

Another question of interest is how to interpret the results, in relation to the requirements for an actual application. In a real drive train the impact loading on a specific gear will depend on complex interactions between different parts of the system, whereas the gear impact test transmits the load directly to the gear. Therefore the test should probably be limited to rank different materials and processes against each other, rather than taking absolute impact values from the test.

It would also be interesting to further evaluate how different gear geometries compare, for instance by varying the tooth root radius. It has been shown [3] that the tooth root stresses can be decreased for powder metal gears by redesigning the root geometry of the gears, and that should also influence the impact strength potentially reducing the distance to wrought steel.

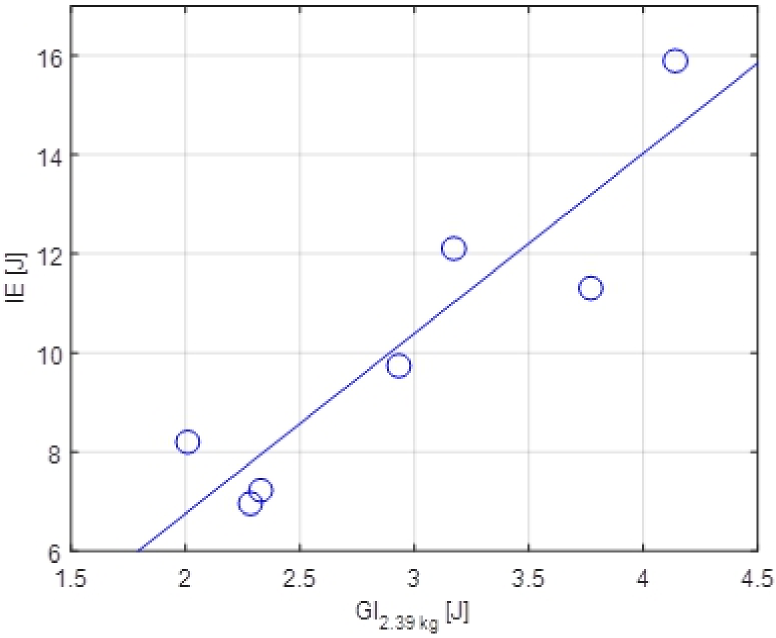

Figure 7. Comparison between gear impact energy and Charpy impact energy.

Conclusions

It was demonstrated how a drop weight type of test can be used to test the impact strength of spur gears. The test method was applied to different PM steels and it was shown that the difference between different materials and densities could be measured. It was also shown that the fracture energy will depend on the weight dropped, and that there is a strong correlation between gear impact strength and a traditional Charpy impact test. It was concluded that the test is best used as a relative comparison between different materials and processes, and could potentially also be used to test how for instance tooth root modification of a PM gear design can increase impact strength.

References

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