Experimental investigation of the strain rate dependence of SS2506 gear steel

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Abstract
Gears are commonly shot peened to increase their fatigue strength without adding weight. The correlation between shot peening parameters, target material and its fatigue behavior is still largely empirical. To further increase the knowledge of shot peening on gear steels and decrease costly experimental investigations this paper compared experimental single indents with carbide balls on Almen strip and gear steel test plates with FEM-simulations. The focus of the investigation was to find a strain rate dependence model including material parameter values that could predict the indent depth at velocities commonly used in shot peening. This was successful for an Almen strip steel (SAE1070) which could be modelled using a Johnson-Cook strain rate model with parameter C=0.035. For the gear steel of type SS2506 (EN 20NiCrMo2-2) the behavior was not entirely captured with any strain rate model. A possible explanation for this was the transformation of retained austenite that was present in the gear steel.

Keywords: Dynamic indentation, shot peening, strain rate dependence

Introduction

Shot peening of gears are used to increase the load capacity without adding weight or space penalties. The relation of shot peening parameters, target properties and the influence on fatigue behavior is still a very empirical knowledge. In order to move towards the possibility to simulate gear fatigue or to gain better understanding of how shot peening influence the target, FEM-simulations of shot peening could be used. Tabor [1] made analytical and experimental contributions to the understanding of static and dynamic indentations. Analytical and numerical models more focused on shot-peening applications were presented for example by Al-Hassani [2], Tufft [3] and Li [4]. A numerical model that gives insight into the concept of coverage was presented by Lombardo and Bailey [5]. Some work has been focused on the modeling of surface roughness from shot peening [6],[7]. Many FEM-models of shot peening have been developed, both 2D and 3D-models. A comprehensive review of shot peening simulations was written by Zimmermann et al. [8].

In shot peening, the deformation rates are very high, up to 10^5-10^6, so strain rate dependencies must be considered [9]. There are several material models developed to include such effects in the stress-strain relations. Two simple ones that are included in the FEM-program that will be used, Abaqus 6.12, are Cowper-Symonds and Johnson-Cook. The Cowper-Symonds relation is shown in Eq. 1 and the Johnson-Cook relation in Eq. 2. Here σ_d is the dynamic yield strength and σ_0 the static yield strength; $\dot{\varepsilon}$ and $\dot{\varepsilon}_0$ are the strain rate and reference strain rate respectively (the reference strain rate was chosen to 1); D,q or C are material parameters.

$$\frac{\sigma_d}{\sigma_0} = 1 + \left(\frac{\dot{\varepsilon}}{D}\right)^{\frac{1}{q}} \qquad (1)$$

$$\frac{\sigma_d}{\sigma_0} = 1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) \qquad (2)$$

The Johnson-Cook relation has a linear increase of the yield strength ratios with logarithmic strain rate. Cowper-Symonds relation can further increase the raise of yield strength ratio depending on the value of q, (see Figure 5 for two examples of this).
The purpose of this paper was to determine material strain rate models and parameters. Experiments with single indents were inverse modeled by simulating the impacts in a FEM-model. Two different targets were used, an Almen strip of material SAE1070 and a case carburized and quenched gear steel of material SS2506 (EN 20NiCrMo2-2). To simplify and remove the influence of the peening media behavior, carbide balls, with hardness above 1700 HV, were used as indenters. Strain rate dependence was then varied in the FEM-model to fit simulation results at corresponding velocities with experimentally measured indent depths.

Experimental Methods

Tungsten carbide balls with 1 mm diameter were shot against a target using a compressed air gun. The target was made of case hardened SS2506 gear steel or an SAE1070 Almen strip of type C. The velocities were varied from around 20 m/s up to 140 m/s. To allow for different sized shot media and a large range of velocities the air gun was custom built, see Figure 1. The velocity just before impact was determined by measuring the time it took for the ball to pass between two photodiodes. The resulting indents were measured with a confocal microscope which gives a 3D image of the surface.

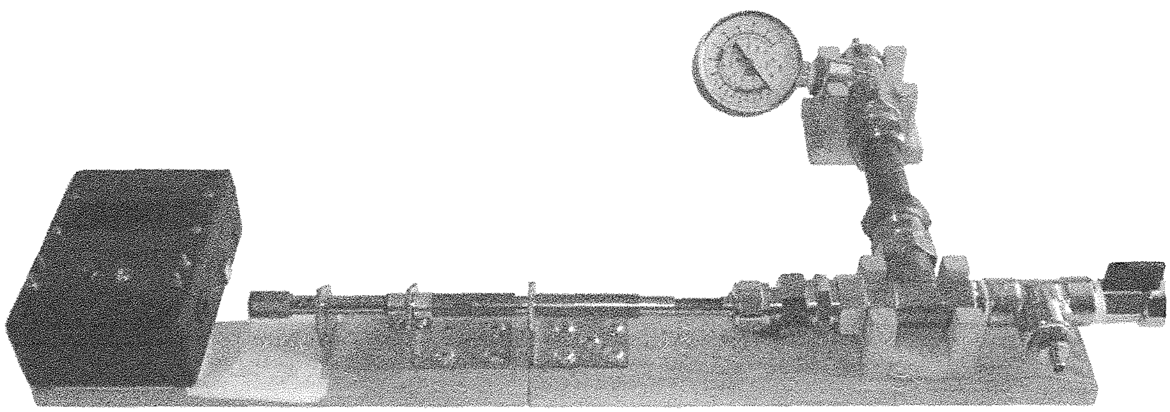
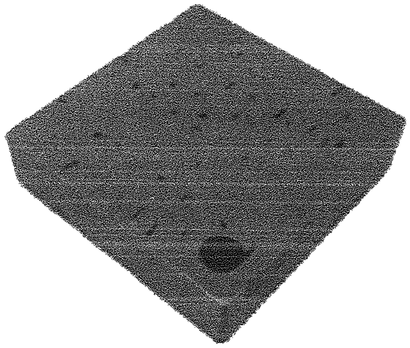


Figure 1 Compressed air gun with velocity measurement device to the left.

The tungsten carbide balls were of grade K20 with a diameter accuracy of ±0.76 µm (acquired from www.comaceurope.com). The density was measured to 14890 kg/m^3 using 100 balls and a laboratory precision scale. Hardness measurements were done by embedding the balls in a mounting resin holder and grinding and polishing the surface to about half the balls diameter. Measurement on about 40 shots gave a mean hardness of 1719 HV and a standard deviation of 50 HV.
Two different types of targets were used. Figure 2 shows the targets of a case hardened gear steel and a standard Almen strip. The Almen strip was embedded in hot mounting resin and polished to mirror finish. Vickers hardness measurements on the polished surface gave a mean hardness of 488 HV with standard deviation of 10 HV using 30 indents at different locations. Standard SAE J442 [10] stipulates a surface hardness of HRC 44-50 which can be converted to approximately 430-510 HV using [11]. The used Almen strip is therefore a little bit above nominal hardness but well within specification. Test plates for the SS2506 gear steel were made with dimension 30x30x10 mm. The plates were case hardened to a depth of 1.7 mm (550 HV) and tempered to a surface hardness of 716 HV. The surface was then polished to mirror finish. Residual stresses and retained austenite was measured with X-ray diffraction equipment Xstress 3000 G3 from Stresstech (www.stresstech.fi). The residual stress was about 120 MPa compressive and the retained austenite amount was about 20%.



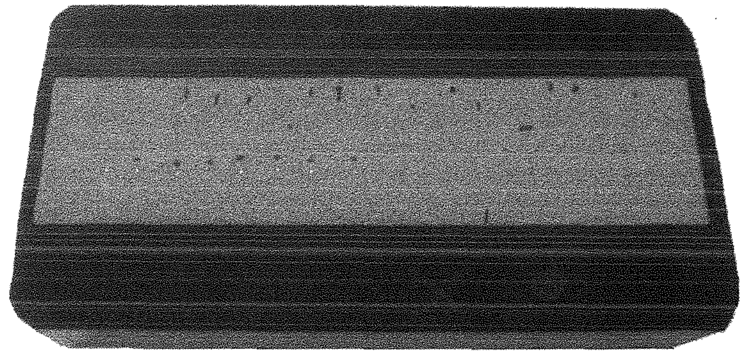


Figure 2 Test plate for SS2506 (left) and SAE1070 Almen C strip (right). Markings on the surfaces are used to identify each individual indent.

The compressed air gun in Figure 1 was used to shoot the balls. To allow the air gun to shoot different sized and irregular shaped shot peening media a sabot was used to hold the projectile. The barrel length was varied between 20 cm or 50 cm with an inner diameter of 8.4 mm. The sabot was turned from POM material (acetal) to an outer diameter of around 8.3 mm that gave it a smooth travel along the barrel but still tight enough to not leak air. A small amount of adhesive from a paper glue stick was used to attach the projectile in the middle of the front side of the sabot. At the front end of the barrel a sabot stopper was used with a hole in the middle to allow the projectile to continue into the velocity measurement device. The air pressure was released into the barrel with a piston valve. The pressure was changed depending in the velocity wanted and varied between 1 bar to 4-5 bar.

Just before the target a velocity measurement was made. The particle passes over two photodiodes. The signal was amplified and connected to an Arduino UNO microcomputer that measured the time and calculated the velocity. The photodiodes were shielded by a 1 mm wide slot to make a precise distance of 68.5 mm between them with an estimated accuracy of ±0.2 mm. The Arduino UNO timer increment every 4 µs which gave the velocity measurement accurate within 1.5 % at 140 m/s (and better at lower velocities). An oscilloscope was also connected to the photodiode amplifiers output to verify the measurement by the Arduino and the quality of the signal.

Indents on the polished surfaces were measured with a PLµ 2300 confocal microscope from Sensofar (www.sensofar.com) which gave a 3D representation of the surface. The measurements were made with a resolution of 0.8 µm spacing between points on the surface and with 0.2 µm spacing in height direction. An example of a measured indent is shown in Figure 3.

Simulation Methods

An axi-symmetric FEM-model, as presented in Alfredsson and Nordin [12], was used to simulate the impact of the carbide ball with the target. The material parameters are shown inTable 1. For the targets each corresponding material curve from compressive stress-strain measurements were used as a table in Abaqus. The carbide was modeled as elastic-ideally plastic and the targets elastic-plastic. Isotropic hardening was used for all materials. Abaqus Explicit 6.12 was used as solver. Each simulation started with an initial velocity of the ball equal to the measured velocity in the corresponding experimental impact. The number of elements in the contact region was chosen to approximately 100. The element size was thus varied for different velocities which creates different indent diameters.

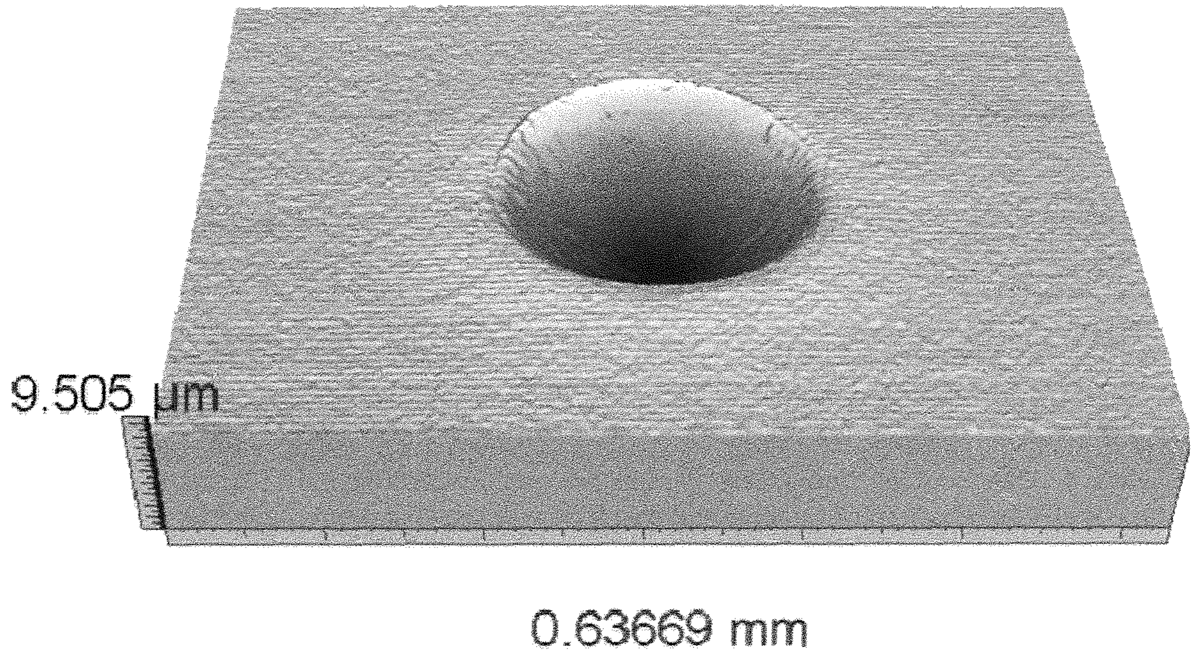


Figure 3 Indent measured with a confocal microscope. Target made of case hardened SS2506 gear steel impacted with a 1 mm carbide ball at 24 m/s.

Table 1: Material parameters used in the simulations.

Material	E-modulus [GPa]	Poisson's ratio	Density [kg/m^3]	Yield stress [MPa]
Carbide	650	0.24	14890	6493
SAE1070	201	0.29	7850	1437 + exp. curve
SS2506	206	0.3	7850	1701 + exp. curve

Results

Figure 4 compares simulated indent depths with experimentally measured results on the Almen strip target. Different strain rate dependences using the Johnson-Cook model was used to fit the experimental data. A strain rate coefficient of C=0.035 gave a good fit over the whole velocity range. Different strain rate coefficients only change the proportional ratio between logarithmic strain rate and yield stress, shown in Figure 4a), which corresponded to changing the proportionality between velocity and depth in Figure 4b). The Johnson-Cook model was therefore an appropriate model for simulating impacts on Almen strips.

Figure 5shows the two models for strain rate, $\dot{\varepsilon}$, dependence used and the comparison with experiment and simulation for SS2506. The experimental indent depths did not have a linear relation with the velocity as the Almen strip did. Therefore the Cowper-Symonds model was also used for comparison. The Cowper-Symonds model can give faster strain rate hardening than the Johnson-Cook model with increasing strain rate dependence. However, judging from the experimental data the depth increased more than linear with increasing velocity. The strain rate dependence should therefore have to decrease with increasing velocity. This was clear from how much the Cowper-Symonds model with q=1 deviate at the highest velocities. Neither of the models could really capture the behavior of the SS2506 steel.

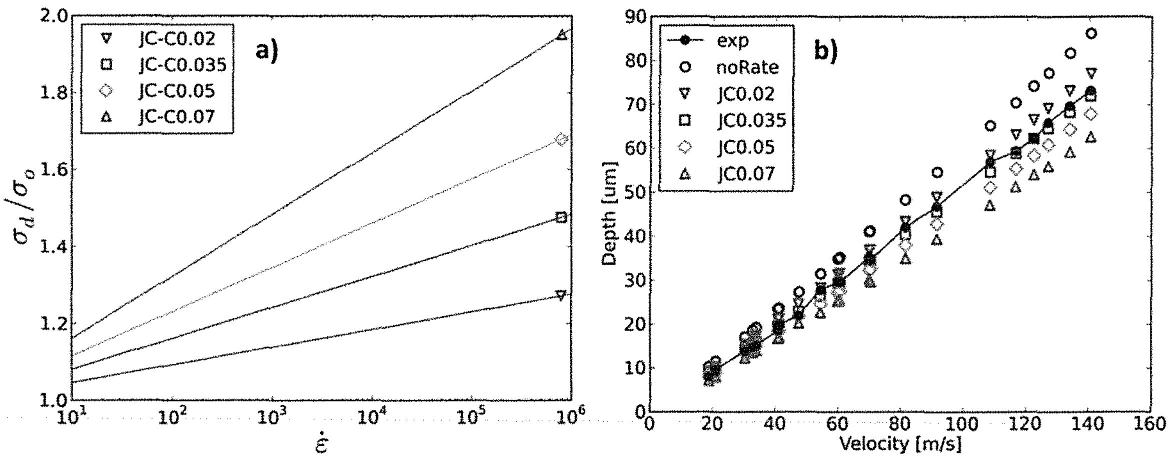


Figure 4: Johnson-Cook strain rate, $\dot{\varepsilon}$, dependence models used to compare simulation to experimental depths on Almen C strips.

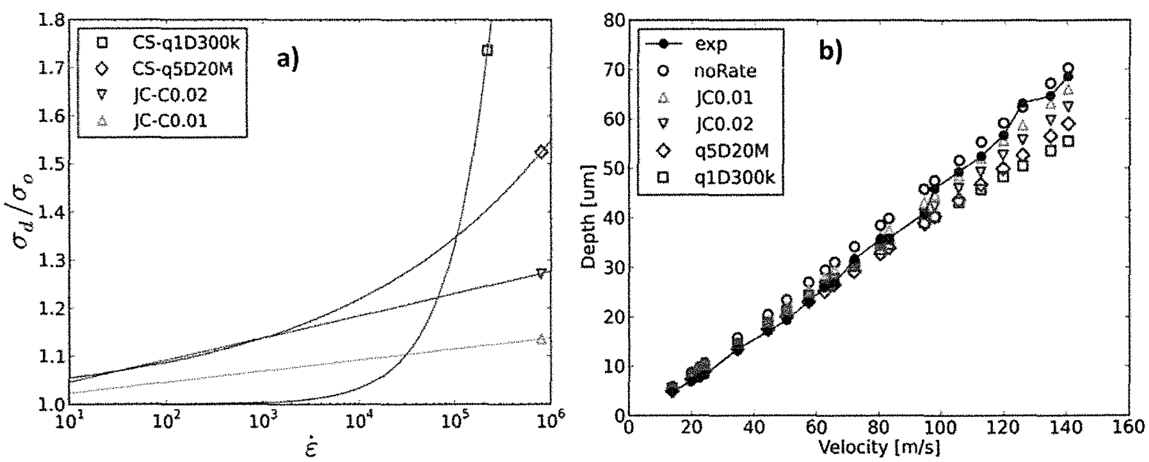


Figure 5: Cowper-Symonds (CS) and Johnson-Cook (JC) strain rate, $\dot{\varepsilon}$, dependence models used to compare simulated indent depth versus experimental depth on SS2506 plates.

Discussion and Conclusions

The indent depth of SAE1070 Almen strip steel could be simulated with a Johnson-Cook type strain rate dependence because the experiments showed a linear relation between indent depth and velocity. The simulations on SS2506 gear steel could not give a satisfying result with any strain rate model. The indent depth increased more than proportionally at higher velocities which mean that the yield strength should actually be lower than anticipated. Neither of the strain rate models allow for this. A physical explanation to why the yield strength decreases at higher velocities could be heat that is developed during the plastic deformation at impact. However, Rouguette et al. [13] shows that while a change in residual stress occur if thermo-mechanical effects are considered, there is no change in which depth they reach. From the indent depth in Figure 5 it can be seen that a material model without any strain rate dependence actually predicts the indent depth good at the highest velocities and the indent depth is overestimated at low velocities. This indicates that there is a process that decrease the energy of the impact at lower velocities but the effect diminishes at higher.

Gear steels are usually on purpose manufactured with a high amount of retained austenite, around 20%, and this was also the case for the SS2506 plates. Retained austenite will transform to martensite during shot peening and this process will consume energy. At high enough impact velocities all retained austenite was probably transformed and the remaining energy would fully contribute to the further increase in indentation depth. To investigate if this was the case the retained austenite could be, as a next research task, transformed by deep cooling the plates in liquid nitrogen and then make new impact tests.

Acknowledgements
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References

[1] D. Tabor, *The Hardness of Metals*, Oxford University Press, London (1951)
[2] S.T.S. Al-Hassani, *Mechanical aspects of residual stress development in shot peening*, Int. Conf. on Shot Peening (ICSP-1) (1981), pp 583-602
[3] M. Tufft, *Shot peening impact on life, part 2: single particle impact tests using production shot*, Int. Conf. on Shot Peening (ICSP-7) (1999), pp 254-263
[4] J.K. Li, Y. Duo and W. Renzhi, *Mechanical approach to the residual stress field induced by shot peening*, Mater. Sci. Eng. A147 (1991), pp 167-173
[5] D. Lombardo and P. Bailey, *The reality of shot peen coverage*, Int. Conf. on Shot Peening (ICSP-6) (1996), pp 493-504
[6] O. Knotek and R. Elsing, *Computer simulation of different surface topographies of metals produced by blasting processes*, Int. Conf. on Shot Peening (ICSP-3),pp 361-368
[7] K. Iida, *Dent and affected layer produced by shot peening*, Int. Conf. on Shot Peening (ICSP-2), pp 283-292
[8] M. Zimmermann, M. Klemenz and V. Schulze, *Literature review on shot peening simulation*, Int. J. Computational Mat. Sci. & Surf. Eng. Vol. 3 No. 4 (2010), pp 289-310
[9] S.A. Meguid, G. Shagal and J.C. Stranart, *3D FE analysis of peening of strain-rate sensitive materials using multiple impingement model*, Int. J. Impact Eng. Vol. 27 No. 2 (2002), pp 119-134
[10] SAE Standard J442, *Test Strip, Holder and Gage for Shot Peening*, http://www.sae.org, 2008
[11] ISO 18265:2003, Metallic materials – Conversion of hardness values, http://www.iso.org
[12] B. Alfredsson and E. Nordin, *An elastic-plastic model for single shot-peening impacts*, Tribology Letters Vol. 52 No. 1 (2013)
[13] S. Rouguette, E. Rouhaud, M. Francois, A. Roos, and J.L. Chaboche, *Coupled thermo-mechanical simulations of shot impacts: Effects of the temperature on the residual stress field due to shot-peening*, J. Mat. Processing Tech. 209 (2009), pp 3879-3886