Shot peening intensity effect on bending fatigue strength of S235, S355 and P460 structural steels

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Abstract. In this study, the effect of shot peening intensity of the structural steel specimens on the bending fatigue strength was investigated. Three structural steels S235JRG2, S355J2+N, P460NH were shot-peened with three levels of intensity. The results of fatigue tests were compared with non-peening processed samples. S-N curves in fatigue were determined in cyclic bending fatigue. The novel attempt to evaluate the bending fatigue, which relies on the 3D optical profiler measurement of the side-area of fractures, was proposed. All investigated steels present ferritic-pearlitic structure. Moreover, due to the peening process, refinement of the grains size was observed. Also, fractures were analysed with the 3D profiler. In the presented results of research, the highest level of peening gave the greater increase in fatigue life. For all types of investigated steels, shot-peening gave superior results of fatigue bending performance compared with unpeened specimens.

1. Introduction
Systematically increasing performance standards impose also more stringent safety standards for machine systems. This fact leads not only to the need to look for a new type of materials, but also to use material treatments to increase strength and durability of existing materials [1–9]. Many deterioration processes such as corrosion, abrasion, sliding, erosion, fatigue wear or even inaccurate maintenance of technological systems, shorten the operation time of industry components [10–18]. Commonly used in the industry are various processing methods for surface layer treatment. Apart from the conventional processes such as heat treatment, carburising or nitriding, the literature reports special treatment processes as laser surfacing [19], ion implantation [20], shot peening [21], thermal spraying [22], physical vapor deposition [23] and many more treatments that increase the operation lifetime of...
components. Despite the variety of treatments listed above, the shot peening technology seems the most cost-effective and promising for implementation into industry conditions. Scholtes and Vöhringer [24] characterises the shot peening process as a method that involves the mechanical interaction of hard particles of shot having sufficient kinetic energy with the surface of a workpiece of given geometry, defined chemical composition, and certain mechanical properties. Shot peening is usually carried out by the wheel method (shot is propelled by a motor-driven bladed wheel) or the air blast method (shot is introduced by an air blast machine, either by gravity or by direct pressure). The attainable near-surface changes in the material are dependent on the shot used, its parameters and type, and the condition of the workpiece [24].

The peening parameters have an influence on the surface layer performance. The metallic materials cause inhomogeneous plastic deformation of near-surface layers which finally result in compressive residual stresses, work-hardening and/or work-softening, or surface roughness development [24]. Shot peening with not accurate process parameters induces roughness on the surface that is linearly proportional to the velocity/intensity of the shot [25]. Thus, intensity of the peening on the operation properties is systematically investigated in the literature e.g. [21,26,27].

Shot peened steel is used for manufacturing the wide variety of components starting from simple structures, casings, machine components, and further for heavy industry and energetics industry. Shot peening is a process specifically designed to enhance fatigue strength of components which are subjected to high alternating stress [28]. The main advantage of the shot peening treatment is the possibility of imparting into the material compressive residual stresses useful from the fatigue life point of view [29–33]. Despite the wide range of research presented in the literature, materials after the treatment of shot peening sharps hard have not yet been adequately tested for fatigue phenomena depending on the process parameters. The type of work based on fatigue bending is especially rare but also needed [14,15,34].

Moreover, many methods for bending fatigue are employed in the industry. Most of them needs time-consuming tests. Therefore, Macek [35] proposed fractal analysis for bending-torsion samples or in the other work [36], presents the idea of fracture surfaces analysis. Thus, in a current paper an original method for evaluation of bending fatigue results is signalised. This method will be suitable for not-fractured samples and especially promising for fatigue samples tested with the failure criterion which is based on exceeding the critical amplitude of lever dislocation.

This study was subjected to untreated and shot-peened specimens made of three steel grades labelled S235JRG2, S355J2+N, P460NH. The main parameter which is guided during the research is the multiplicity of the re-process (process intensity) [27,37]. The material is subjected to a single, double, and threefold shot peening process of the surface.

The main aim of the study was to investigate the effect of shot peening intensity of S235, S355 and P460 steels on bending fatigue strength. Moreover, the new method for evaluation of bending fatigue strength with usage of computer methods that basis on an optical profiler results analysis, is presented.

2. Materials and methods

2.1. Materials

The materials used in this study were 12mm sheet metals made of three steel grades labelled as S235JRG2, S355J2+N, P460NH according to EN10028 and EN10025-1 standards [38]. In the following part of the work, in order to simplify the recording, the following designations were adopted: S235, S355 and P460. The mechanical properties of investigated materials are shown in Table 1 and the structure of the steel was observed on metallographic samples and quantitatively analysed with usage of Matlab software [38–40].
Table 1. Mechanical properties according to the manufacturers’ certificates.

| Material | Yield stress, Re (MPa) | Ultimate stress, Rm (MPa) | Young modulus, E (GPa) | Elongation, A (%) | Re/Rm | Hardness, HV |
|----------|------------------------|---------------------------|-----------------------|------------------|-------|-------------|
| S235     | 291.0                  | 424.5                     | 210                   | 30.0             | 0.69  | 132         |
| S355     | 391.0                  | 516.0                     | 213                   | 33.0             | 0.76  | 160         |
| P460     | 616.5                  | 717.0                     | 205                   | 24.6             | 0.86  | 212         |

2.2. Shot peening process and structure characterisation

The main parameter which is guided during the research is the multiplicity of the re-process (i.e. the process intensity). The material was subjected to a single, double, and threefold shot peening process. The steel-ball shot stream was propelled at 0.7 MPa. The peening process lasted about 4 minutes, shot granulation was 0.75-0.85 mm. The process was carried out under industrial conditions with comparable to the literature parameters [40–42]. The specimens were treated from four sides of the working part. The samples were subjected to a single, double, and threefold shot peening process of the surface. The surface quality of the peened samples was examined using optical microscope and optical profiler. The microstructure of the processed surface layer was observed on metallographic cross-sections with the usage of a light optical microscope.

2.3. Cyclic bending test

The fatigue research was carried out on the MZGS-100 fatigue test stand [39,43,44]. The tests were carried out under loading with the controlled force and loading frequency 28.8 Hz. The fatigue tests were performed under the stress ratio R = -1. The object of the study consisted of specimens with geometry and dimensions shown in Figure 1. Samples were cut from sheets 12 mm plate in thickness according to the rolling direction. 15 specimens of each material were prepared. Investigated specimens were subjected to different values of bending moment (cyclic bending test) [16,45,46]. The failure criterion was based on exceeding the critical amplitude of lever dislocation [47–49]. Statistical analysis of Stress-Life (S-N) fatigue data was performed according to ASTM standard [50].

![Figure 1. Dimensions of the specimen used for cyclic bending.](image)

2.4. Characterisation of surface of peened samples with computer methods

Metallographic examinations of shot peened samples were made using the optical microscope [51,52]. The surface morphology surface analysis was performed using an optical 3D test stand Alicona G4 facilitating the acquisition of data sets at a high depth of focus according to the procedure described in [53]. The morphology of each steel peened with different peening intensity were comparatively analysed. The surface roughness parameters Sa, Sq, Ssk, Sku, Sp, Sv and Sz, calculated according to the ISO standard were compared on the basis of measurements done in specific areas of damage surfaces. Moreover, the failure analysis of the samples was conducted with usage of the optical profiler and special software which allows to conduct the analysis relating to surface morphology development.
3. Results and discussion

3.1. The effect of shot peening on structure and surface morphology

Three investigated types of structural steel, namely: S235, S355, and P460, presented ferritic-pearlitic structure however the microstructure of each steel differed in size of initial grain size visible in the core area in cross-sections of shot-peened in Figure 2. Also, quantitative metallographic results given in [39], confirmed decreasing volume content of ferrite (15.7%, 29.6% and 37.9%) and decreasing ferrite grains size (22.96%, 6.97% and 4.54%) for samples S235, S355 and P460, respectively. Analysis conducted after shot-peening process confirmed that the surface layer was deformed due to peening process, Figure 2., and refinement of the grains size was observed. The comparative analysis of the morphology of the shot peened surfaces indicated the influence of intensity on the surface layer structure Figure 3.

![Figure 2](image2.png)

**Figure 2.** Metallographic cross-sections of specimens after shot peening a) S235, b) S355, c) P460.

![Figure 3](image3.png)

**Figure 3.** Characterisation of the surface plastic deformation due to intensity of the shot peening process of S235 steel. a ) 1-single, b) 2-double c) 3-trefold peening d) comparison of surface morphology for various process parameters.
3.2. Fatigue tests results
Statistical analysis results of Stress-Life (S-N) fatigue data performed according to ASTM E739 standard, are presented in Figure 4. Thus, the plots compared peening intensity on the fatigue resistance.

General conclusion is that the S235 steel shot peening process increased the bending fatigue life of tested steel S235, S355 and P460 samples in reference to unpeened steel, Figure 4. However, due to the spread of the fatigue test results, it is difficult to clearly state the effect of peening process intensity on the bending fatigue. In the case of S355 steel, shot peening process increased the fatigue life of the material. In the case of two-times, there was a decrease in fatigue life compared to one and three-times. The reason for reduction of the fatigue characteristics after two-times peening may be the spread of results. Accuracy of constructed characteristics can improve the testing of more samples. The metallographic analysis of the material after two-times shot peening indicated occurrence of numerous microcracks caused by the selection of incorrect parameters of the process, which could have also affected the fatigue life of the specimens. Failure of shot peened steels under fatigue may be caused by crack propagation starting at locations where surface structural non-uniformities occurred, which were observed at the samples cross-sections. P460 steels showed a slight increase in fatigue life after the one-time process. After two and three-time shot peening, an increase in durability was observed, however, the indication of differences between durability for individual multiples of the process is difficult due to the dispersion of experimental studies.
Figure 4. Fatigue characteristics of the untreated and shot peening processed steels S235, S355 and P460 with different process intensity.
3.3. Fractographic investigation with usage of an optical profilometer

After a series of fatigue tests, it was observed that the shot peening process improved the fatigue properties of the specimens. During fatigue tests, the materials cracked in narrow places, which allowed observation of cracks. All materials, both S235 and S355 as well as P460, after subsequent shot peening, cracked identically, i.e. the initiation of fatigue cracking occurred in the upper or lower part of the cross-section, which is presented in Figure 5. However, in the case of Steel P460 after a three-fold process shot peening in the range of a small number of cycles, i.e. 60-70 thousand samples were bursting analogously to those described earlier. But in the case of samples whose service life exceeded considerably one million cycles, the material cracked in the upper and lower part of surface of the tested specimen. It was a characteristic feature only for this material.

![Figure 5. Surface fatigue-cracks (marked by arrows) after triple shot peening, S235, S355 and P460.](image)

The 3D surface investigation allows to identify the crack and complete the crack analysis. In Figure 6 the exemplary sample side scan, see Figure 1, is presented. Surface topography measurement was made after bending test on the radius-side of the sample, see Figure 6. The profilometer technique clearly visualise cracks and area of the fatigue deformation. In Figure 7 the exemplary comparison of fracture areas is presented. The comparison of the centre area with the near crack area provides important information about the fracture mechanism and fracture resistance. The aim of this paper is to just signalise the idea and methodology of the investigation, thus it can be deduced from Figure 7 that the elaborated idea works and provides interceding information for fracture result interpretation especially for propagation mechanism. This quite unique attempt for bending fracture results analysis invented by Macek [35,36] is now being developed and will be published in our future work.

![Figure 6. 3D view presenting the crack propagation after bend testing.](image)
**4. Conclusions**

In the presented work, the effect of shot peening intensity of S235, S355 and P460 steels on bending fatigue strength was examined.

All examined steel grades an increase in fatigue life with respect to the reference (unpeened) material was noted. Shot peening for all tested steel grades had a positive effect in the case of low-cycle fatigue (LCF) and for single shot peening process.

In LCF range the highest level of peening gave the greater increase in fatigue life. In fatigue the intermediate level of peening gave results similar to those of the high level peening. These results are explained in terms of observed the surface damage.

The new method for evaluation of the bending fatigue strength with usage of the computer methods, that basis on the optical profilometer results analysis, was suggested.

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