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THE EFFECT OF SHOT PEENING ON THE FATIGUE STRENGTH OF SPRING ELEMENTS[1]

Bruno Kaiser, Dr.-Ing.
Institute for Materials Technology
Technical College of Darmstadt
Darmstadt, West Germany

Introduction

The favorable effect of shot peening on the fatigue strength of components of the most diverse kind, in particular springs, can be approximately optimized, if the shot peening factors, such as the kind of the shot peening system, the shot peening intensity and time, shot peening media (shape, hardness), surface covering of the workpiece and other features are taken into account. These factors were described in detail by the author in a separate treatise (Kaiser, 1986).

Setting Parameters and Characteristic Values of Shot Peening

Figure 1 (Martin, 1982) shows in diagrammatic form the way in which the important setting parameters of the shot peening plants together with the properties of the blasting media and the treated material alter the surface layer of the treated material and, therefore, the component properties, especially the fatigue strength properties. To achieve the highest possible fatigue strength, these parameters must be optimized and compliance with these parameters in production must be monitored (Krickau, 1975). This is accompanied by an attempt to describe the effect of shot peening by easily measurable characteristic values. Despite frequent criticisms and numerous other proposals, the shot peening intensity is still usually measured by the so-called Almen test. To this end, standardized plates, with an area of 76 mm. × 19 mm., of cold-rolled spring steel of a hardness of 44 to 50 Rockwell are clamped and shot-peened on one side. The curvature ("height of arc") of the Almen strip measured after unclamping gives a measure of the shot peening intensity and has proved to be a good process control method and a criterion for setting up shot peening plants (Lepand, 1965; Krickau, 1975). The test strip must be arranged so that it always covers important regions of the component (for example, the inner turns of helical springs).

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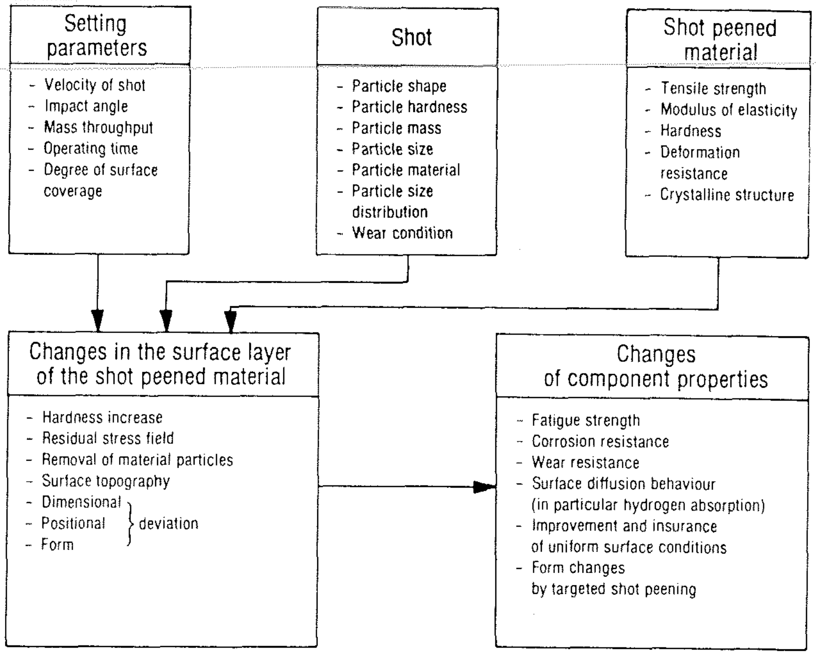


Fig. 1. Diagrammatic view of the effects of shot peening on the component properties (see Martin, 1982).

Three test strips of different thickness, N (0.785 mm.), A (1.295 mm.) and C (2.385 mm.) are used to cover the entire range of different material tensile values and component thicknesses, as well as different shot peening intensities, determined in accordance with the Almen test. Given the same shot peening intensity, each thinner strip will curve three times as strongly as the next thicker strip.

Unfortunately, no direct relationship has as yet been established between the Almen intensity and the degree of fatigue strength increase of the shot-peened components. According to (Krickau, 1975), this is due to the following:

—There is no relationship between component changes due to shot peening and the Almen arc height;

—the change of Almen arc height must be evaluated in conjunction with the degree of coverage obtained on the workpiece;

—the effect due to material properties, for example, workhardening characteristics and notch impact sensitivity, cannot be accounted for;

—the same Almen arc height can be achieved, despite differences in the formation of residual stresses (Spigiel, 1983);

—the arc height does not account for the roughness texture of the surface.

An unequivocal determination of the increase of fatigue strength of springs obtained by shot peening, therefore, calls for fatigue tests.

In addition to the Almen test, the rate at which the component surface is covered represents an important characteristic for evaluating the shot-peening treatment.

"Covering" relates to the percentage proportion of the surface area on which the shot peening media impinges. The degree of surface coverage increases with an increasing shot peening time and approaches asymptotically to the limit of 100 percent. A value of 98 percent is usually taken as complete coverage and the associated shot peening time is $t_{98\%}$. Longer shot peening times can be given as a multiple of the value of $t_{98\%}$. Coverage and the number of shot peening passes (shot peening time) is expressed by the following relationship:

$$C = 1 - (1 - C_1)^n.$$

In this expression, C = surface coverage after n passes, expressed as % of the theoretical maximum values of 100 percent, n = number of shot peening passes or shot peening time units, and C_1 = surface coverage after one shot peening pass or after one shot peening time unit.

The degree of surface coverage can also be determined by planimetric means or by comparison with reference series; another possibility is the so-called "peen-scan" process (O'Hara, 1985): a fluorescent liquid, which forms a brittle film on the surface to be treated, is locally broken and detached by impinging shot peening medium, so that places of insufficient coverage can be made visible by ultraviolet illumination (Schutz, 1986).

The Significance of Residual Compressive Stresses Caused by Shot Peening on the Fatigue Strength of Springs

Shot peening changes the surface hardness, residual stress condition, and surface texture (Strigens,

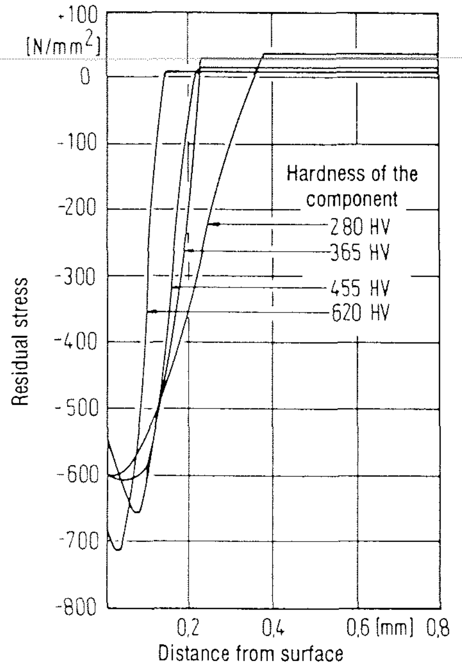


Fig. 2. Effect of component hardness on the setting up of residual stresses (see Niku-Lari, 1975). HV = Vickers hardness.

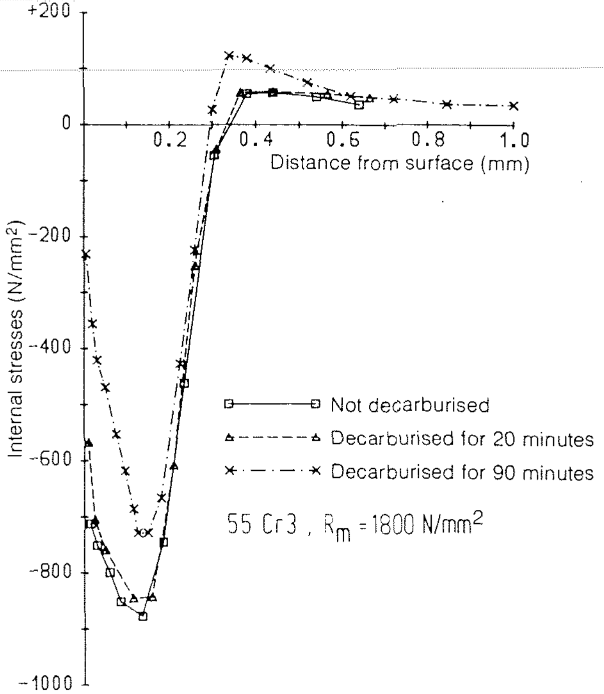


Fig. 3. Change of depth of residual stresses of round specimens with different decarburization and uniform shot peening.

1971; Macherauch, 1980; Kaiser & Kosters, 1982; Wohlfahrt, 1982; Scholtes, 1986; Schutz, 1986) in the surface zone of treated components. The increase of hardness plays practically no part in this group of components (except for parts having surface decarburization) in view of the high initial hardness of springs. In the same way, the relatively slight roughening permitted by the high tensile values can usually be neglected. Producing a layer of residual compressive stresses in the surface zone of the shot-peened component, where in an extreme case the maximum value can also reach the yield point of this zone, is decisive for increasing the fatigue strength of springs treated by shot peening. Figure 2 shows how the depth of the layer containing residual compressive stresses diminishes with an increasing initial hardness (Lepand, 1965; Niku-Lari, 1975; Martin, 1980) if the shot peening parameters are kept constant.

The following general conclusions (Hirsch et al.,) can be drawn from published results of investigations on the formation of residual stresses in material specimens and components subjected to shot peening:

—The amount of residual shot peening stresses on the surface of the treated material is determined in the first place by the tensile strength or hardness of the material. Peening parameters, such as the velocity of the shot, the degree of coverage, and the diameter of the shot only slightly affect the amount of residual compressive stresses on the surface of the shot-peened workpiece.

The maximum amount of residual compressive stresses induced by shot peening sets up usually below the surface of the shot peened material. The maximum residual compressive stress is shifted toward the surface of the shot-peened material only in cases of low tensile values of the material and/or low shot peening intensities.

The thickness of the surface layer containing residual compressive stresses increases for all material hardness values with an increasing velocity of the shot, size of the shot, and rate of coverage.

In hardened shot-peened material (hardness > 700 Vickers) and all other shot peening parameters remaining the same, the transition from a soft (460-530 Vickers) to a hard (580-655 Vickers) shot increases the amount of surface stress and of the maximum residual stresses, as well as the thickness of the surface layer containing residual compressive stresses.

In shot peened material with notches compared with smooth material subjected to the same degree of shot peening, residual stress depth distributions will be formed below the surface of the notch bottom with a maximum residual compressive stress which is localized and of greater magnitude.

In Müller (1985) it was found that the shot-peening conditions for workpieces free of incipient cracks should best be selected so that the maximum residual compressive stress is situated on the surface. However, if a component already contains microcracks, it should be shot peened, so that the residual compressive stress zone extends as far as possible into the component.

Changes of Shot Peening Dependent Residual Stresses Caused by Pulsating Torsional Stresses

The effect of shot peening on the pulsating torsion strength of spring steel specimens 55Cr3 (material No. 1.7176) with different surface decarburization and surface oxidation was investigated by Kloos & Kaiser (1981) (diameter 14 mm.; $R_m \approx 1850$ N/mm.^{2}).

Shot peening resulted in improvements of fatigue strength by 20 percent for previously polished specimens, up to 65 percent for surface decarburized specimens, and up to 100 percent for surface oxidized specimens.

Residual stress measurements by X-rays on specimens from the same batch and with the same tensile value but with different degrees of decarburization, without work-hardening, as well as after shot peening and after the application of pulsating torsion stresses (Kloos et al., 1981) have, in the meantime, been the subject of a test program. Specimens without shot peening feature residual tensile stresses in the surface zone and these rise from approximately 250 to 350 N/mm^2 with an increasing decarburization time. Figure 3 shows three characteristics of residual stress depth of specimens with different decarburization and subsequent uniform shot peening with $A_2 =$ 0.52 mm., residual stresses in the longitudinal and circumferential direction being equal. This shows that comparable residual compressive stress maxima are obtained below the surface and diminish slightly with increasing decarburization, despite different starting conditions. The residual stress values on the surface itself evidently react more distinctly to surface decarburization.

In evaluating residual stresses relative to the fatigue strength of components, it is always important to inquire whether and to which degree the residual stress systems, which existed prior to stressing, are retained during fatigue stressing. For this reason, the present investigation includes specimens which were also subjected to pulsating torsional stresses after surface decarburization and shot peening.

This pulsating torsional stress over 3×10^5 cycles with 500 ± 400 N/mm^2 after shot peening reduces the residual stress values numerically in the circumferential and axial direction (Fig. 4).

If measurements of residual stresses are made in several directions to the specimen axis, it will be seen that the residual stress condition is rotated into a principal stress system located at 45° to the specimen axis. At the same time, residual stresses in the σ_1 (tensile) direction remain practically unchanged while in the compressive direction σ_2 they are clearly displaced toward smaller values (Fig. 5).

For the direction σ_1, this result can be explained by superimposing residual compressive stresses of -800 N/mm^2 due to shot peening on a mean load stress of $+500$ N/mm^2 and a resultant combined stress of -300 ± 400 N/mm^2 which takes place completely within the elastic range of the specimen material (Fig. 6). In the σ_2 direction, on the other hand, residual compressive stresses due to shot peening (-800 N/mm^2) are superimposed on a mean compressive stress of -500 N/mm^2 and on the cyclic stress at -1300 ± 400 N/mm^2 (assuming an ideal elastic response of the material). However, a shift of the residual stresses in this stress direction is understandable, since the measured torsional yield point amounts to 1100 N/mm^2.

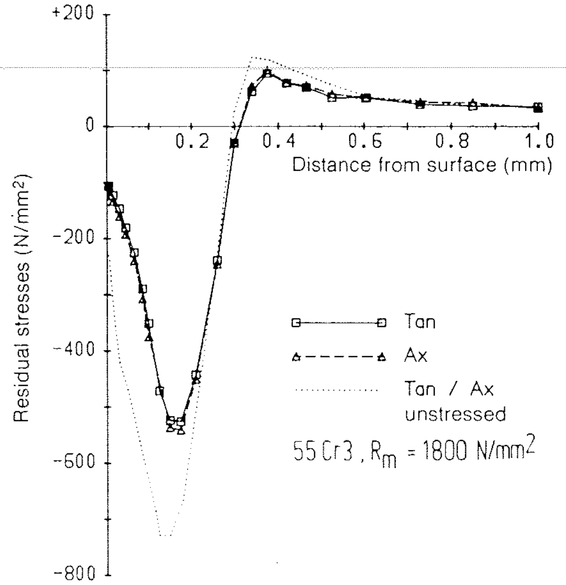


Fig. 4. Change of internal tangential and axial stresses of a specimen under pulsating torsional stress with shot peening and decarburization of 90 min.

The important residual compressive stress in the critical σ_1 direction (tensile load stresses) is, therefore, retained and contributes to an improvement of the fatigue strength characteristics.

Shot Peening of Leaf Springs or Parabola Springs Under Prestress (Prestressed Shot Peening)

The basic condition governing the formation of residual stress conditions in components is the plastic flow of individual zones of the material. In shot peening, the energy required to this end is produced by the shot particles which are accelerated onto the workpiece surface; the effectiveness depends on the share of converted plastic energy. To produce plastic deformation energy, a basic amount of elastic energy must first be applied to produce plastic deformation energy in shot peening treatment without prestress. The share of plastic deformation energy in shot peening without prestress is therefore relatively low, since the predominant amount of energy is applied to plastic deformation (Siekmann).

Prestressed shot peening

An improvement can be achieved by so-called prestressed shot peening, in which layers of parabola springs under substantial prestress are subjected to shot peening. If the component is prestressed close

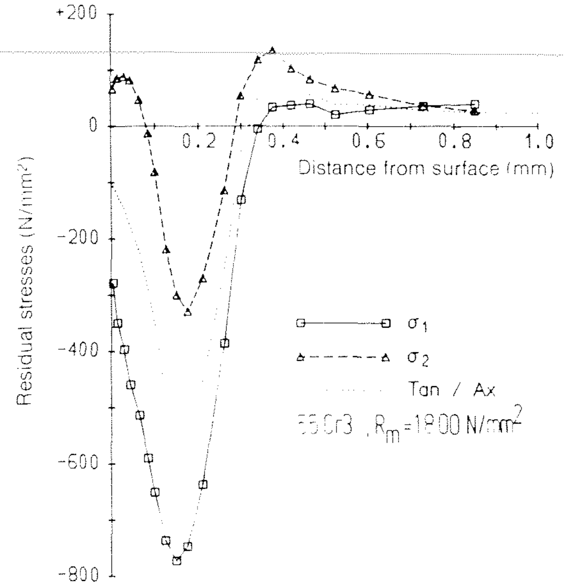
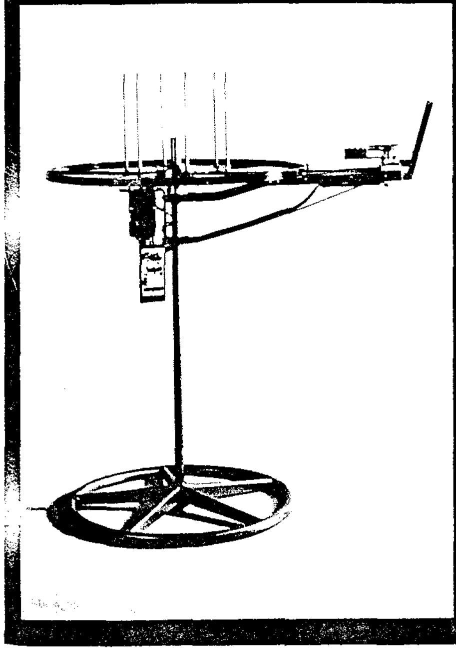


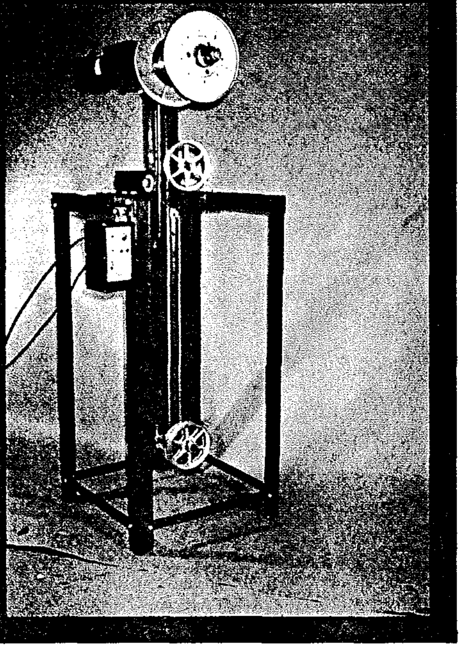
Fig. 5. Change of depth of residual stresses in the principal stress directions σ_1 and σ_2 at ± 45° to the specimen axis.

to the 0.2 percent yield strength of the material, practically the entire kinetic energy of the shot can be converted into plastic deformation energy and heat. This results in the formation of a favorable residual stress condition (Spigiel, 1983). If the shot-condition without prestress is compared with conditions under tensile prestress of between 700 and 1350 N/mm.^{2}, it is found that residual surface stresses increase with a rising tensile prestress. The residual compressive stress maximum is shifted in like manner toward higher values (O'Hara, 1985).

In prestressed shot peening, which is in some cases applied even during the production process of highly stressed parabolic springs, the individual leaves pass through the shot peening plant in U-shaped boxes, open at the top, in which they are loaded with a theoretical prestress of 1600 N/mm.^{2} in the direction of the subsequent operational stress and retain their ultimate shape during the entire shot-peening process. In this way, the greater part of preliminary scragging will have been carried out and when the spring leaves are unclamped, the applied prestress is at least partially added to the residual compressive stress produced by shot peening. Altogether, the following approximate values are, therefore, obtained for prestressed shot peened springs: 700 to 800 N/mm.^{2} at the surface and approximately 1200 to 1400 N/mm.^{2} at a depth of 0.15 to 0.25 mm. below the surface (both values measured along the longitudinal axis).

The zone near the surface on the tensile side of the parabolic spring leaves is, therefore, so intensively compressively prestressed that no further plastic





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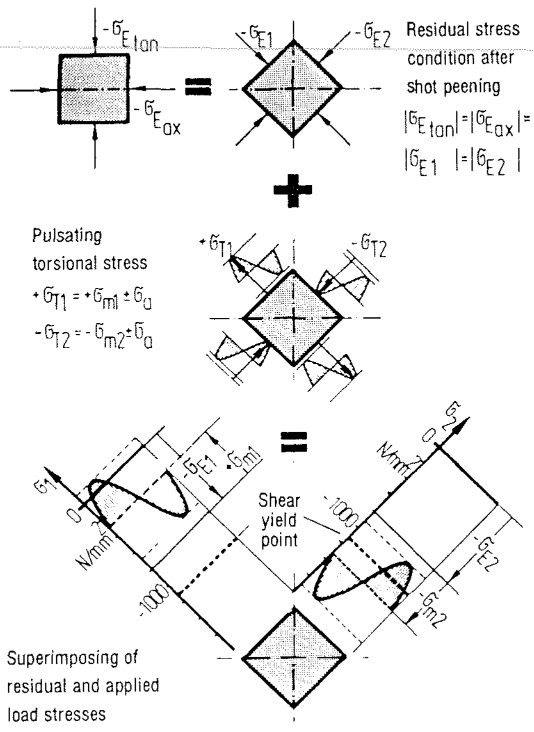

Fig. 6. *Superimposing of residual shot-peening stresses and pulsating torsional stresses in the surface zone of a round specimen after quenching and tempering (for an idealized elastic material characteristic).*

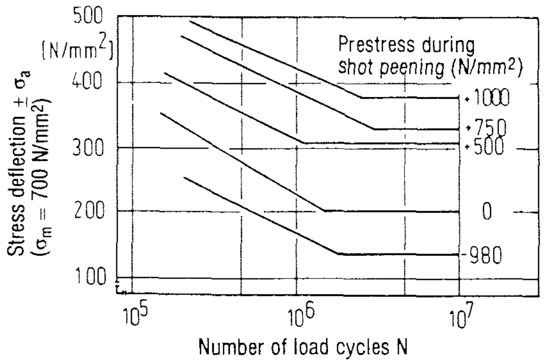

Fig. 7. Wohler curves of prestressed, shot-peened leaf spring specimens (see Xu et al., 1982).

deformation occurs despite the large strain, even during the subsequent prescragging, and the residual stress condition is retained. Since the residual compressive stresses produced by prestressed shot peening are substantially higher than the full load and, in some cases, are even greater than the stress produced by bearing against a stop, it is possible for the service life of parabolic springs to be increased by a multiple of the original values (Robinson & Smart, 1984). This is because high tensile stresses, which could lead to incipient fatigue cracks in operation, become ineffective or are effective to only a small degree on the particularly sensitive surface of the leaf and in the surface zone immediately below (Estorff et al., 1986).

The results of fatigue tests on leaf springs subjected to shot peening under prestress are also presented in (Xu et al, 1982) (material 55 Si Mn V B, $R_m \approx$ 1430 N/mm.², specimen cross section 9 × 75 mm²., surface decarburization depth 0.13 to 0.16 mm.). Figure 7 shows the Wöhler curves obtained for different prestresses in shot peening and Figure 8 shows the associated residual stress characteristics. Residual compressive stresses induced by shot peening clearly increase with an increasing prestress and, therefore, also improve the fatigue strength. As in Kloos & Kaiser (1981) incipient fatigue cracks were found on the surface despite the shot peening treatment. This is assumed to be due to the effect of the decarburized layer. Reports on similar improvements of the durability of shot peened components obtained by prestressing during shot peening are also described in Oicles & Landecker (1950), Kuehn[illegible] (1982), N.N. (1983), and Robinson & Smart (1984).

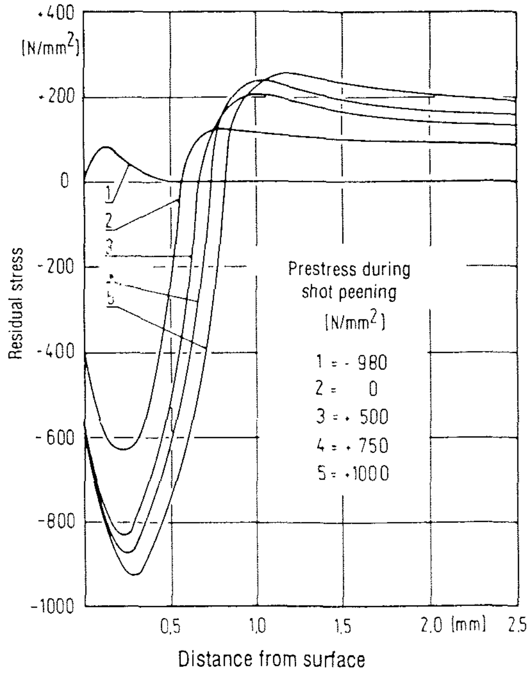

Fig. 8. Change of residual stress of prestressed, shot-peened leaf spring specimens (see Xu et al., 1982).

Examples Illustrating the Increase of Fatigue Strength of Springs and Spring Steel

To summarize, Figure 9 shows some examples illustrating the increase of fatigue strength of springs and spring steel specimens obtained by shot peening for different starting conditions. This clearly shows that depending on material, shot peening conditions, specimen diameter, stress, etc., shot peening can achieve an improvement from between 10 and 15 percent up to more than 100 percent. Once again it is shown that, given relatively optimized starting conditions, shot peening can, of course, achieve only a limited improvement, but that minor surface defects, due to the manufacturing process or unavoidable for economic reasons, can be substantially eliminated or compensated for by subsequent shot peening. In these cases, the originally very low fatigue strength can be very greatly increased.

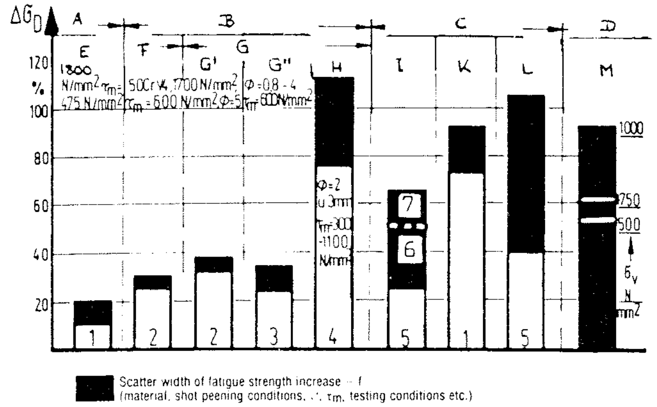

Fig. 9. Increase of fatigue strength obtained by shot peening of springs and spring steel specimens with different starting conditions (1 according to Kloos & Kaiser, 1981; 2 according to Kaiser, 1981; 3 according to Hirose, 1982; 4 according to Baao et al. 1984; 5 according to Watkinson, 1956; 6 according to Buch and Chodorowski, 1967; 7 according to Oicles and Landecker, 1950; 8 according to Xu et al., 1982.)

Key: A = polished; B = cold drawn, cold coiled; C = surface decarburized; D = hot rolled; E = specimen, 14 mm.; F = wire, quenched and tempered; G = helical springs; G′ = quenched and tempered; G″ = patented drawn; H = Austinitic; I = surface decarburized; K = decarburized and surface oxidized; L = surface oxidized or network; M = improvement over shot peening through stress shot peening.

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