Influence of the shot peening angle on the condition of near surface layers in materials

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Introduction

There are only few investigations (1-3) concerning the influence of the angle of impingement which is an important parameter in the shot peening of structural parts. (2) indicates an angle between 70° and 85° which results in an optimal peening effect without variation of the other parameters. In this range, (1) also determines the largest penetration depth at constant shot velocity. In contrast to this, (3) states that the normal component is the only parameter responsible for the formation of the indentation. Accordingly, the deformed layer decreases with decreasing peening angle.

The aim of these investigations was to examine the influence of a peening angle different from 90° by means of a detailed analysis of the near surface layers. The basis of the examinations was not a single indentation, but rather a shot peened surface with complete coverage. The material investigated was the plain carbon steel Ck 45 both in a normalized and in a quenched condition. The investigations include the analysis of the distribution of residual stresses and half-width values using X-ray measurement methods as well as the examination of the texture of the near surface layers and the bending fatigue behaviour.

Experimental Procedure

The investigations were carried out with a plain carbon steel (German grade Ck 45; chemical composition 0.52 % C, 0.24 % Si, 0.61 % Mn, 0.01 % Cr, 0.02 % Mo, 0.04 % Ni, 0.02 % V, 0.029 % S, 0.01 % P). The specimens were taken out of a rolled sheet material of 6 mm thickness. For the bending fatigue tests, the size of the specimens was 110×24×2 mm and for X-ray measurements 110×20×2 mm. Some of the specimens were treated at 860 °C for 10 minutes and oil quenched at 40 °C. The other specimens were normalized at 845 °C for 1 hour. All specimens were ground to their final thickness after heat treatment for the purpose of removing surface oxidation.

The shot peening treatments were carried out with an air-blast machine. For the investigations, a cast steel shot S 330 with a hardness of 55 to 58 HRC was used at a pressure of 3 bar and a coverage of 100 %. The distance between nozzle and specimens was held constant (80 mm) for every peening angle.

The residual stresses of the specimens were determined by X-ray measurement using a ψ-diffractometer and applying the $\sin^2\psi$-method. The measurements where a ψ-splitting appeared were additionally interpreted with an extended evaluation method (4). For this purpose, the residual lattice strains of ⟨211⟩-planes were analyzed with CrKα-radiation. The residual stresses were measured both in longitudinal ($\phi = 0^\circ$) and in transverse direction ($\phi = 90^\circ$). The stress measurement of the subsurface layers was carried out after removing layers on both sides of the specimen. For this purpose, a chemical polishing technique was applied. The measured stresses were corrected (5). The half width values were taken out of interference line profiles for $\psi = -9^\circ$, 0° and $+9^\circ$. The measurements of the texture were carried out with a computer controlled ψ-diffractometer which allows the determination of intensities for ϕ-angles from 0° to 360° and ψ-angles between -70° and $+70^\circ$.

For fatigue tests, cyclic bending was applied in mechanically driven bending fatigue machines (Schenck) with a sinusoidal load-time-function. For each S/N-curve, five suitable stress levels were chosen and tested with at least five specimens. The bending fatigue tests were stopped when a specimen had reached 10^7 cycles. The experimental results were interpreted using an arc sin-$\sqrt{p}$ - transformation, p being the probability of fracture.

Experimental Results

Fig. 1 shows corrected residual stress distributions in longitudinal ($\phi = 0^\circ$) and transverse ($\phi = 90^\circ$) direction for both the normalized and the quenched condition. For normalized specimens which were shot peened in perpendicular direction ($\alpha = 90^\circ$) the largest maximum residual stress (σ_{max}^{RS}), the highest surface residual stress (σ_S^{RS}) and the largest penetration depth were determined (Fig. 1a). The position of the maximum stress below the surface also shows a maximum value. For decreasing peening angles, the values of the parameters mentioned above also decrease. Fig. 1b shows the residual stress distributions in transverse direction ($\phi = 90^\circ$). For decreasing peening angles, increasing maximum residual stresses were observed as well as increasing surface values. In contrast to this, the penetration depth and the position of the maximum stress obtain smaller values. A comparison between the residual stress distributions for $\phi = 0^\circ$ and $\phi = 90^\circ$ shows that with a peening angle < 90° the maximum stresses in transverse direction are closer to the surface than the stresses in longitudinal direction. However, the residual stress

	peening angle	σ_S^{RS} [N/mm^2]		σ_{max}^{RS} [N/mm^2]		HW$_S$ [deg.]	fatigue limit [N/mm^2]
		$\varphi=0^\circ$	$\varphi=90^\circ$	$\varphi=0^\circ$	$\varphi=90^\circ$		
normalized	90°	-378	-378	-385	-385	3,0	306
	45°	-302	-378	-358	-440	3,24	291
quenched	90°	-440	-420	-994	-968	2,97	755
	45°	-348	-398	-856	-869	3,0	746

Tab. 1: Characteristic data of residual stress, half widths and fatigue limits

distributions are similar in the regions greater than 0.15 mm below the surface. For different peening angles the residual stress distributions determined at quenched specimens are shown in Fig. 1c (for the longitudinal direction $\phi = 0$) and in Fig. 1d for the transverse direction ($\phi = 90^{\circ}$). In both directions, the residual stress distributions are, however, nearly similar for adequate peening angles. If the peening angles decrease, the maximum stresses and the penetration depths also obtain smaller values. The position of the maximum stress shifts towards the surface. The surface stresses decrease slightly. In Tab. 1, the characteristic residual stress data are listed for peening angles of 45° and 90°. Fig. 2 shows the half-width values for normalized and quenched specimens with peening angles of 45° and 90° respec-

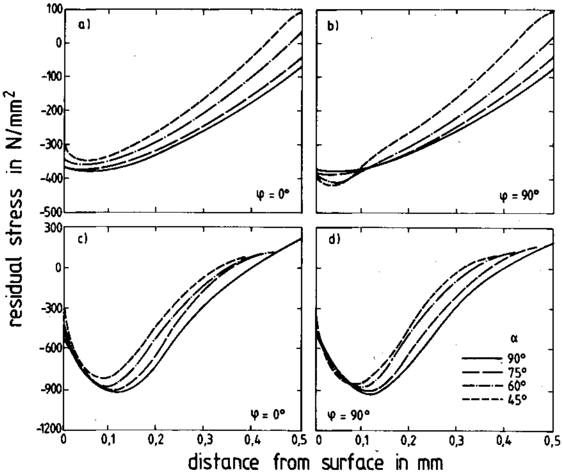

Fig. 1: Residual stress distributions for longitudinal ($\phi = 0^{\circ}$) and transverse ($\phi = 90^{\circ}$) direction for different peening angles ($90^{\circ} \leq \alpha \leq 45^{\circ}$) in the normalized (a, b) and in the quenched (c, d) condition.

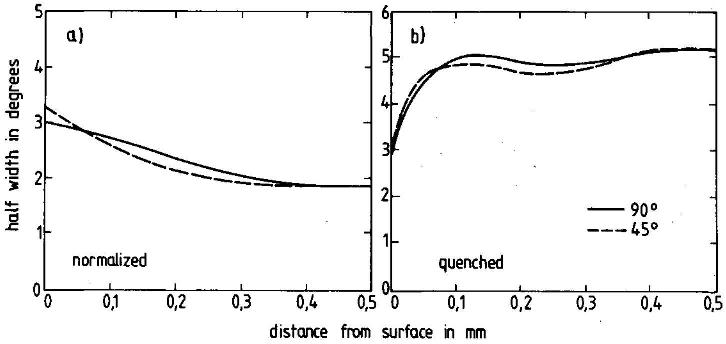

Fig. 2: Distributions of half width values for the normalized (a) and the quenched (b) condition for peening angles of 90° and 45°.

tively. If normalized specimens are shot peened using a peening angle of 45°, a stronger surface hardening effect can be observed than using a peening angle of 90° (Fig. 2a). At a greater distance from the surface, however, the values for perpendicular peened specimens are higher. Fig. 2b illustrates the distribution of the half-width values for quenched specimens. At the surface, the values decrease strongly. The lines for 45° and 90° do not show a significant difference.

Fig. 3 illustrates the texture of normalized Ck 45 before and after shot peening. The pole figures in the upper part of the figure are those of the ⟨110⟩-planes of the ferrite and the pole figures in the lower part of the figure those of the ⟨211⟩-planes. Fig. 3a shows the texture of ground samples before shot peening. The resulting texture is typical for grinding soft materials. After perpendicular shot peeening (α = 90°), a quite different texture state is observed (Fig. 3b), i. e. a ⟨110⟩-fibre texture can be found. The specimens which were shot peened with an angle of 45° show a texture analogous to that appearing after perpendicular peening (Fig. 3c). However, the poles were tilted by an angle of 16°.

S/N-curves determined at normalized specimens shot peened using a peening angle of 45° and 90° are shown in fig. 4a. It is interesting to compare these curves with the S/N-curve of ground specimens (6). Shot peening leads to an improvement of the fatigue limit and to an increase in fatigue life . It is quite obvious that perpendicular shot peening leads to a higher lifetime of the specimens than peening with an angle of 45°. In the case of quenched specimens, improvements obtained by shot peening with both a peening angle of 90° and of 45° were similar.

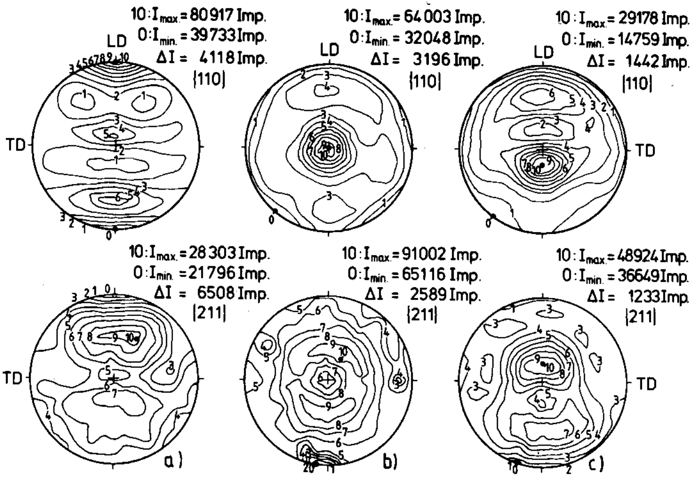

Fig. 3: Texture pole figures of ⟨110⟩-planes and ⟨211⟩-planes of ground (a), 90° shot peened (b) and 45° shot peened (c) specimens in the normalized state.

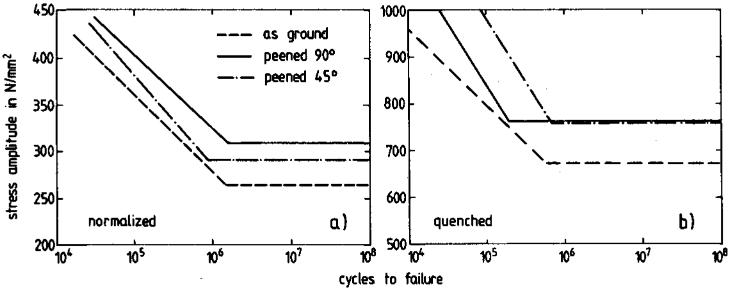

Fig. 4: S/N-curves of normalized (a) and quenched (b) specimens in ground and shot peened (α = 90°, 45°) condition.

Discussion

The near surface condition of a shot peened material is mainly dependent on the processes occurring during shot peening (6). These are partly compression procedures during which the near surface layer is plastically deformed. As a result, a compressive residual stress state occurs which starting with a maximum amount at the surface is characterized by rapidly decreasing residual stress amounts or which shows in the near surface area at first constant stress values and then decreasing ones. An example for the second phenomenon is shown in Fig. 1a for perpendicular peening (α = 90°).

An additional aspect is the process of Hertzian pressure (7). The normal component of the impact load causes a maximum shear stress below the surface and the existing yield strength will be exceeded. The resulting inhomogeneous plastic deformations cause compressive residual stress distributions whose maximum value lies below the surface. During shot peening, principally both processes appear, however to different degrees(6).

For the normalized condition different residual stress distributions in longitudinal and in transverse direction are observed in the case of a constant peening angle. The analysis of longitudinal stresses resulted in the determination of ψ-splittings occurring at peening angles $\alpha < 90°$ and up to a depth of 0.15 mm. This is exemplarily shown in Fig. 5 for a surface measurement using a peening angle of α = 45°. The ψ-splitting is caused by a principle axis system tilted over the transverse axis of the specimen. The area in which this splitting can be observed is identical with the area in which the measured transverse stresses deviate from the longitudinal stresses. A further interpretation of the measuring data (4) resulted in the determination of the existing principal stresses and the shear stresses. Fig. 6 illustrates the measured stress distribution as well as the calculated distribution of the principal stresses and shear stresses for a peening angle of 45°. The tilt angle of the principal axis system is 4.9° and the shear stress in the surface layer obtains maximum values of 30 N/mm². It can be concluded that the principal stresses differ only slightly from measured surface parallel stresses, which means that they are considerably smaller than

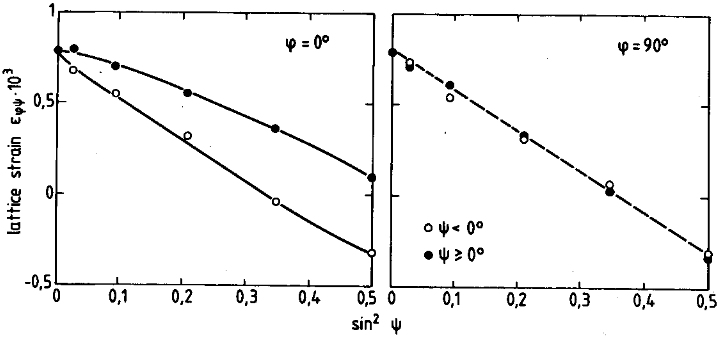

Fig. 5: Distributions of the lattice strain for normalized specimen after shot peening ($\alpha = 45^{\circ}$) for longitudinal ($\Phi = 0^{\circ}$) and transverse ($\Phi = 90^{\circ}$) direction.

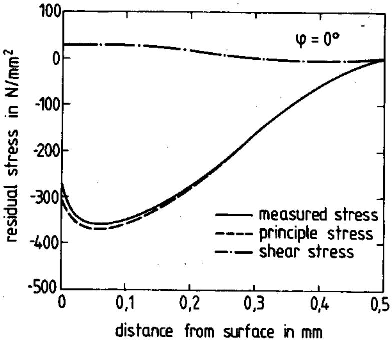

Fig. 6: Measured stress, shear stress and principal stress in longitudinal direction ($\Phi = 0^{\circ}$) after shot peening ($\alpha = 45^{\circ}$) in the normalized condition.

the values measured in transverse direction ($\Phi = 0$). Thus, the tilting of the principal axis system itself is not a satisfying explanation for the difference between the longitudinal and transverse stress distribution. The real reason for this phenomenon will most probably be found in deformation procedure occurring in the surface layer during peening.

If one examines the texture state of the surface, some conclusions can be drawn concerning the process of plastic deformation. Starting from the grinding texture as shown in Fig. 3a, a fibre texture develops during vertical shot peening (Fig. 3b). The upper pole figure shows that ⟨110⟩-planes are mostly arranged parallel to the surface around the normal direction. This means that in soft materials the process of surface deformation mainly takes place in the ⟨110⟩-slip planes. The compressed surface layer is deformed circumferentially around the indentation and parallel to the surface.

If the peening angle is changed to 45°, one also observes a change in the texture state (fig. 3c). In this case, the poles are inclined at an angle of 16° with respect to the specimen normal. This means that in longitudinal direction the deformation is no longer parallel to the surface. It can as well be stated that the orientation of the crystals is stronger in longitudinal direction and weaker in transverse direction. Thus, it can be concluded that there are different deformation processes in longitudinal and in transverse direction.

A comparison between the half-width values of specimens shot peened with an angle of 45° and of 90° (Fig. 2a) shows that 45° peened specimens reveal a stronger hardening in the near surface layers than the 90° peened ones. A qualitative consideration of the deformation process allows an explanation of the development of the residual stress state. As described above, after peening with an angle of 45°, different deformation processes in longitudinal and in transverse direction can be supposed. In a soft material the shot moves tangentially on the surface, when it impinges at a small angle. As a consequence, in longitudinal direction the upsetting before the indentation is stronger than behind it and stronger than the upsetting after a perpendicular indentation. This process of upsetting, which is due to a plastic compressive deformation, causes areas with tensile residual stresses. Thus, an integral measurement of stresses in longitudinal direction shows smaller compressive residual stress values for 45° peened specimens than for 90° peened samples. In transverse direction additional to the upsetting a shearing of material appears caused by the tangential movement of the shot. Thus, the compressive residual stress values are higher than in perpendicular peened specimens. Both mentioned deformation processes produce the observed stronger hardening of the near surface layer of 45° peened samples with respect to vertically peened ones.

In other machining processes, there are also stress distributions which are different in longitudinal and in transverse direction. Especially in the case of grinding with a small feed, compressive residual stresses of different magnitude occur (8, 9). It can be observed that the deformation process shows some analogy to that occurring during shot peening with small peening angles, especially with respect to the movement of particles tangential to the surface. The difference, however is, that in the case of grinding, a much greater tangential force and an additional cut of the material is observed. The fact that during the grinding process, compressive stresses of different magnitude in longitudinal and transvers direction occur is explained similar to the above described processes (8).

In contrast to the normalized material condition, in the quenched condition there are no differences between the residual stress distributions measured in longitudinal and transverse direction with the same peening angle (Fig. 1c, 1d). This is a realistic result, because for hard material conditions the normal component is the most important influencing parameter during the formation of residual stresses. The position of the stress maximum below the surface is determined by the contact area between shot and specimen. The maximum stress value depends on the existing normal impact force (6). The impact force decreases with decreasing peening angle. Thus, the contact area between shot and specimen also decreases. This result corresponds to the observed decrease of the stress maximum and its shift to the surface. Measurements with peening angles of $\alpha = 90^\circ$ and 45° revealed that there are no differences between the half-width values. According to former investigations (10, 11), the measured values decrease in near surface layers.

Shot peening results in an increase in fatigue strength and fatigue life. In the case of normalized specimens this effect is more pronounced after peening with an angle of 90° than with 45°. Residual stresses occurring in soft materials decrease rapidly during cyclic loading and are therefore of no practical importance for the bending fatigue behaviour. Consequently,the above described behaviour of the material must be a result of the different hardening processes of the surface layer. As illustrated in Fig. 2a, in materials shot peened with 90°, a thicker surface layer is affected. The observed behaviour is plausible taking into account the fact, that the crack growth in the near surface layers is impeded stronger in 90° peened specimens than in 45° peened specimens.

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