ACADEMIC STUDY
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Component Distortion
An Overview

INTRODUCTION

Every shot peener distorts components—if only in the form of Almen strips. They would be useless if they didn't distort! Distortion is caused by a combination of plastic deformation and induced residual stresses. Force, rigidity and bending moment determine the amount of distortion. This article aims to explain, for non-experts, how distortion in a shot peened component develops.

Shot peening is a cold-working process so that plastic deformation and residual stress development go hand in hand. Each imposed residual stress system must involve a balancing of both forces and bending moments. Force is the level of stress multiplied by the area over which it acts. It is important to distinguish between the magnitude of stress and the force to which it corresponds. Fig. 1 illustrates this basic relationship. Imagine a typical eating apple being suspended from a beam using wire of 1 mm^2 cross-sectional area. Assuming the apple imposes a force of 1N on the wire, then we have a system with a stress level of 1MPa induced into the wire (1Pa = $1Nm^{-2}$). The wire is being strained by the applied force. Residual compressive surface stresses in peened components are generally in hundreds of MPa with core tensile stresses in tens of MPa. Note that it is forces that generate stresses—not the other way round. The distribution of residual stresses in a peened component depends upon the balance of forces and bending moments that are a consequence of the peening operation.

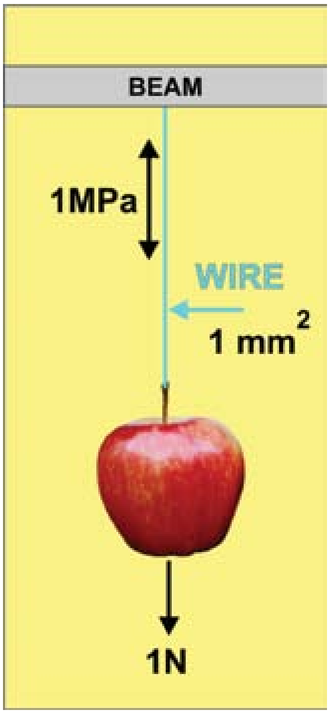

Fig. 1. Simple residual stress system.

Heyn introduced a simple spring model in 1912, purportedly as an aid to understanding balancing of residual stresses. A spring model has been introduced in this article to simulate the necessary balancing of forces and bending moments that must exist in a shot-peened component.

SYSTEMS OF FORCES AND BENDING MOMENTS

Stable, Balanced System

Fig. 2 represents a stable system. Imagine two compressed springs each pushing end blocks outwards with a force of 10N. These two forces are balanced by ten stretched springs symmetrically placed above and below the centerline and each pulling the end blocks inwards with a force of 2N. We now have a balanced, stable system of forces. There is no tendency for the two end blocks to move. The system of forces/bending moments is roughly similar to that in a strip that has been peened on both major faces by equal amounts. Peening would have induced equal compressive forces, F, on the upper and lower faces balanced by tensile force, 2F, acting on the core. This system is represented in fig. 3 which includes analogous springs.

Unstable, Unbalanced System

Fig. 4 represents a spring model of an unstable system. The model is the same as that shown as fig. 2 but with the lower,

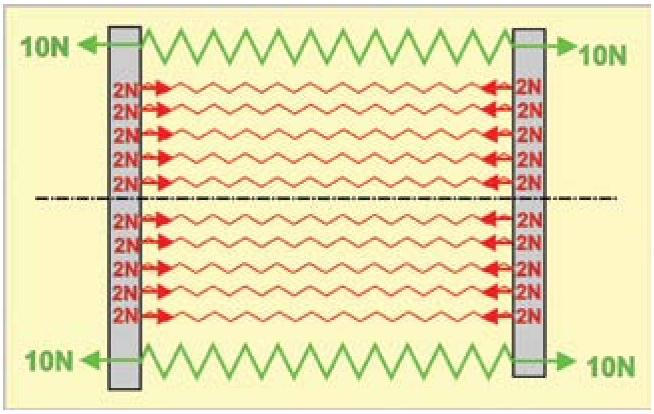

Fig. 2. Spring model of a stable, balanced, force/bending moment system.

compressed spring removed. Removing this spring gives an imbalance of both forces and bending moments.

Stable, Balanced System

In order to correct the situation of fig. 4, spring forces would adjust themselves to give the stable situation shown in fig. 5. The force in the remaining compressed spring is reduced. As the end blocks rotate about their axes, the forces change in the originally stretched springs. Those above the centerline increase whereas those below the centerline reduce with some eventually becoming compressive.

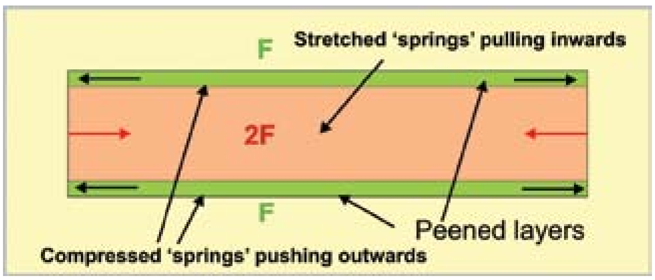

Fig. 3. Stable, balanced, force/bending moment system for a peened strip.

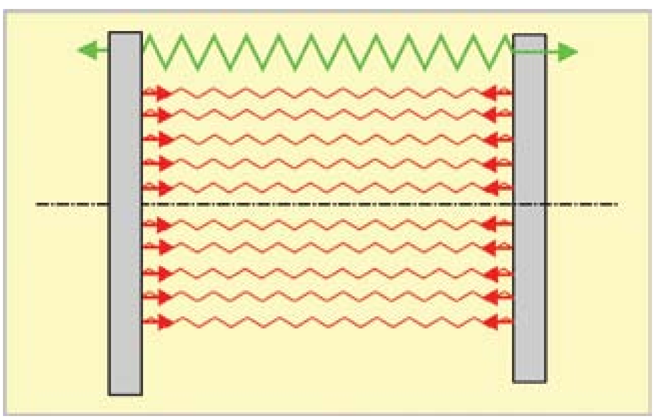

Fig. 4. Spring model of an unstable situation.

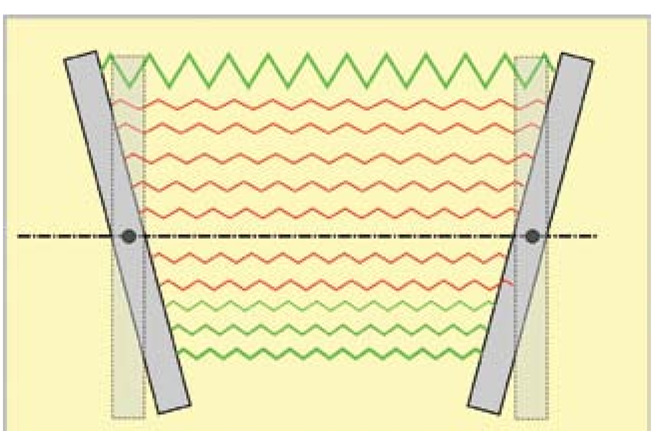

Fig. 5. Spring model showing adjustments needed to achieve a stable situation.

The equivalent peened situation to that of fig. 5 is shown in fig. 6. Strip bending is induced by the force, F, being exerted by the peened layer. This force is the product of residual stress level multiplied by the area over which it acts. Fig. 7 shows a typical distribution of residual stress in the surface region. Consider, as an example, that this distribution was from a peened Almen strip. Since the strip dimensions are well-known (19 mm x 76 mm) we can estimate the longitudinal and transverse compressive forces. Assuming an average stress of 240N mm^{-2} in the compressed surface layer we have the longitudinal force is some 19 mm x 0.5 mm x 240N mm^{-2} or 2280N, and the transverse force is some 76 mm x 0.5 mm x 240N mm^{-2} or 9120N.

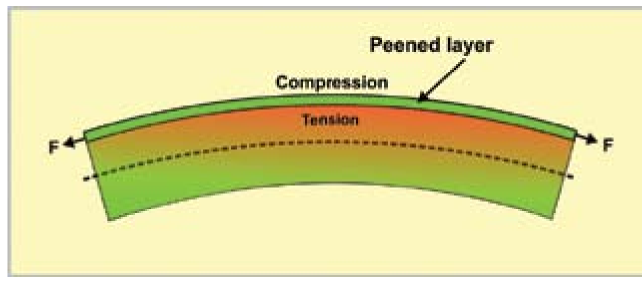

Fig. 6. Peened strip equivalent of Fig. 5.

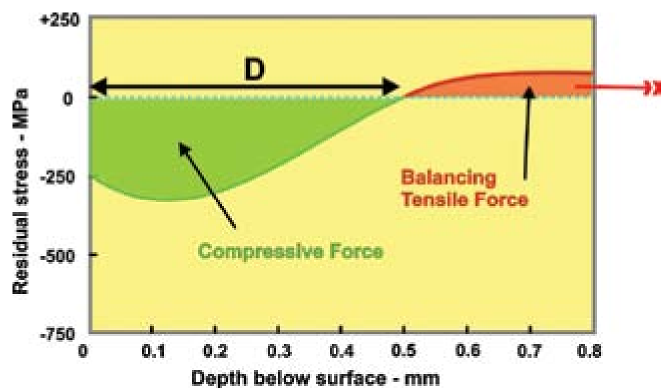

Fig. 7. Typical residual stress distribution near peened surface giving rise to compressive and tensile balancing forces.

DEVELOPMENT OF RESIDUAL STRESSES AND FORCES

Residual stresses and corresponding forces can only develop as a consequence of cold-working. By definition, hot-working is carried out at such a high temperature that the worked component self-anneals. Inhomogeneous cold plastic deformation is a necessary requirement for residual stresses and forces to develop. Shot peening is a process that involves cold-working of the surface of components. The plastic deformation involved is confined to the peened surface. This means that peening plastic deformation is "inhomogeneous". In effect, only the peened surface is plastically deformed.

There is a universal "Golden Rule" defining the sign of the residual stress that is induced by inhomogeneous plastic deformation:

The sign of the residual stress is the opposite of the sign of the inhomogeneous plastic deformation that caused it.

The "sign" of peening surface plastic deformation is positive (+) equivalent to tensile deformation. Applying the "Golden Rule," the resulting surface residual stress must be compressive (-).

We can think of peening as inducing surface residual stress forces that are the equivalent of compressed springs. The force in the "springs" increases with (a) the depth of the peened layer and (b) with the average stress in the peened layer.

The tensile surface plastic deformation of peening is the sum of numerous miniature surface movements. Fig. 8 is a simplified portrayal of the surface movement associated with an individual dent. The material present before denting, ABCA, is pushed sideways, i.e., parallel to the surface. This corresponds to tensile, (+), plastic deformation of the peened surface layer and therefore to a compressive residual force. The core material resists this outward movement requiring a balancing tensile force.

DUPLEX BENDING CAUSED BY PEENING

So far, only bending in one direction has been considered. Denting causes tensile stretching in the two directions defining the surface. The easiest way to appreciate this duplex bending is to consider a peened Almen strip as shown in fig. 9. Peening bends the strip by an amount corresponding to h1 parallel to the strip's major axis AB. A smaller amount of bending, h2, also occurs parallel to the strip's minor axis BC. Almen strip and gauge manufacturers would not be in business if this type of bending did not occur! It is also worth noting that peening must induce component distortion—to a greater or lesser extent—but more on that later.

DISTORTION AND RIGIDITY

Distortion will normally occur as a consequence of shot peening. The only exception will be if the operation is

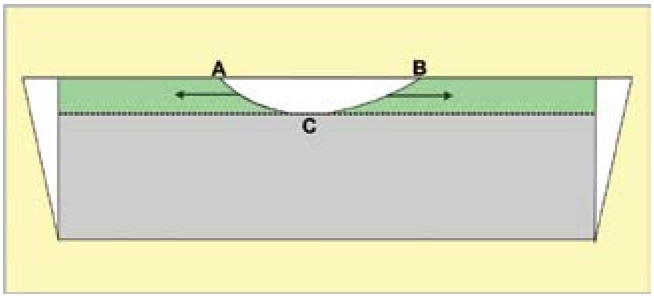

Fig. 8. Simplified portrayal of material movement caused by a dent.

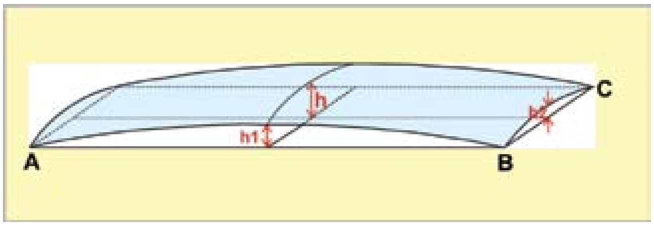

Fig. 9. Duplex bending induced by peening one major surface of an Almen strip.

absolutely homogeneous; for example, if both major faces of an Almen strip were peened simultaneously using identical peening parameters. The extent of the induced distortion depends upon the magnitude of the bending force and the rigidity of the component.

Rigidity is determined by the geometry of a component's ***cross-section***. The difficulty of estimating component rigidity seems to increase exponentially with the complexity of its geometry. Some appreciation of the most important factors can be obtained by using a simple example. Consider trying to bend, using only fingers, a steel ruler as illustrated in Fig. 10. Common-sense/experience tells us that with this orientation the induced bending will be negligible. The ruler is exhibiting high rigidity. On the other hand, if we rotate the ruler through 90˚, bending will occur quite easily. The two orientations correspond to A and B in fig. 10.

The simplest relationship for rigidity, **I**, is that of a rectangular object. Its width, **w**, is multiplied by the cube of its thickness, **t**, and divided by twelve. Expressed as an equation:

$$\mathbf{I = w.t^3/12} \qquad (1)$$

Assume, for the sake of simplifying mental arithmetic, that the ruler's cross-sectional dimensions are 20 mm x 2 mm. For the orientation A shown in fig. 10, the width (normal to the page) is 2 mm and the thickness is 20 mm. Hence I = 2 mm x 20^3 mm^3/12 or 16,000 mm^4/12. Rotating the ruler through 90˚ to give orientation B means that the width now becomes 20 mm and the thickness becomes 2 mm. Hence I = 20 X 2^3 m^{m4}/12 or 160 m^{m4}/12. The "edgewise" orientation, A, therefore has a rigidity value 100 times as great as the "flatwise" orientation, B. This quantifies the difference in our ability to induce bending.

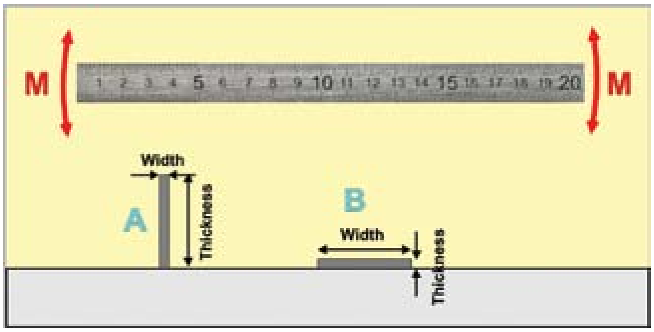

Fig. 10. Bending moment, M, being applied to a steel ruler.

The primary conclusion is that **thickness is the key factor in determining the onset of distortion** because rigidity is a function of the **cube** of thickness. As we know, an Almen N strip, being thinner, distorts much more than an Almen A strip when given the same amount of peening.

PLASTIC VERSUS RESIDUAL STRESS DISTORTION

As mentioned earlier, distortion is caused by a combination of plastic deformation and induced residual-stress forces. Fig. 11 illustrates the situation for a simple shape such as an Almen strip. The two contributions to deflection, plastic (pl) and residual stress (rs) are roughly equal. That ratio has been confirmed by noting the 50% reduction in arc height that occurs when stress-relief annealing has been applied to peened strips. Potential distortion estimated from residual stress force can be doubled to give a predicted total distortion value.

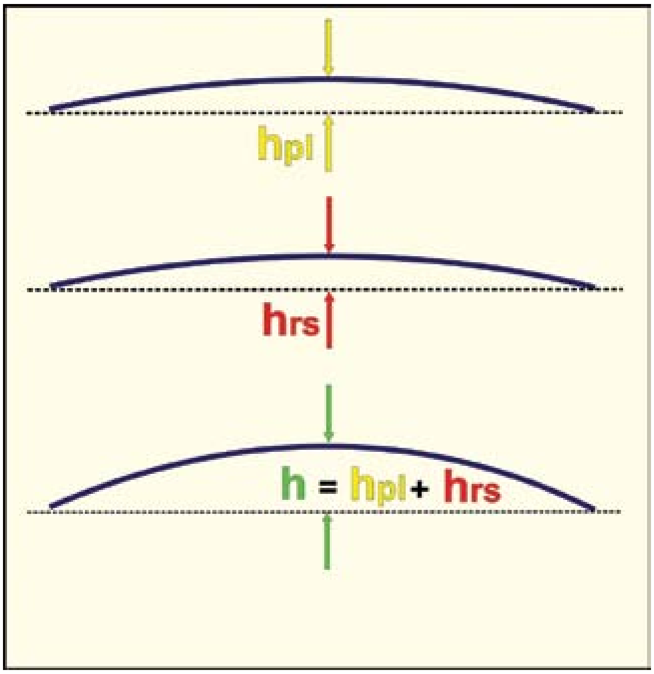

Fig. 11. Strip distortion components for peened Almen strips.

FACTORS CONTROLLING DISTORTION ARISING FROM RESIDUAL STRESS

Three factors control the amount of distortion induced by residual stress forces. These are: BENDING MOMENT, RIGIDITY and ELASTIC MODULUS. Increase of bending moment increases distortion whereas increases of rigidity and/or elastic modulus reduce distortion. This is illustrated schematically in fig. 12.

A quantitative relationship, familiar to mechanical engineers, exists that links the three factors:

$$1/R = M/(E \times I) \qquad (2)$$

1/R is the curvature induced by applying the bending moment, M, E is elastic modulus and I is rigidity. The larger the value of M/(E x I) the greater will be the induced curvature.

The relationship factors are illustrated in fig. 13 for a shot-peened strip. Note that bending moment, M, is a function of force, F, multiplied by strip thickness.

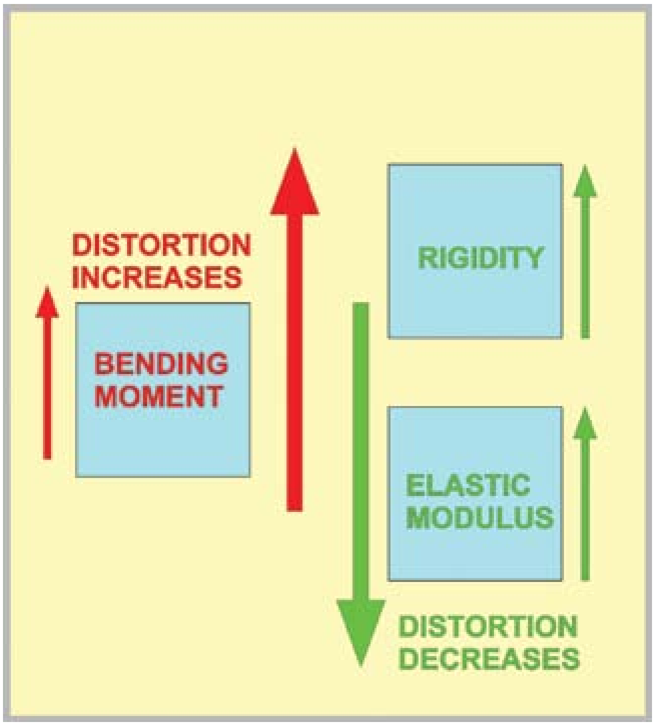

Fig.12. Factors controlling distortion.

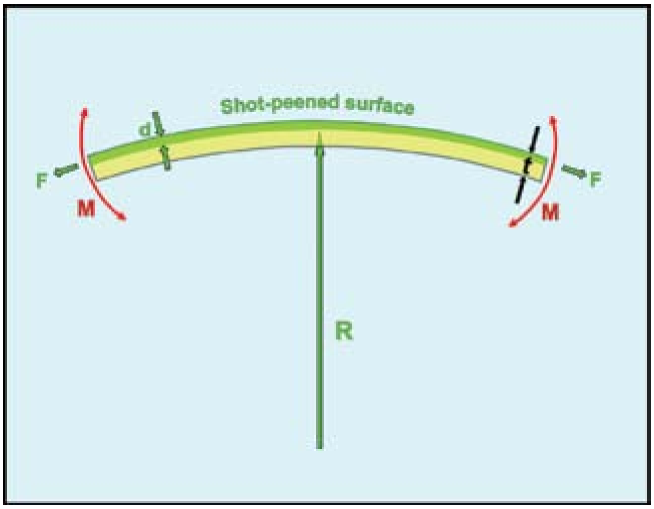

Fig. 13. Inter-relationship of factors affecting distortion of a strip.

1/R is called the "curvature" of the distorted object. The larger the value of 1/R the larger is the curvature and therefore the amount of distortion. Curvature is generally preferred to deflection as a quantitative measure of distortion because it is independent of the component's length. Imagine standing on a plank supported at its ends. If the plank was 10 m long the induced deflection would be much greater than if it was only 2 m long. Almen strips are a special case because they are always of a fixed length. Their distortion is quantified by the deflection from flatness—arc height. Distortion of an originally flat component can readily be measured using a feeler gauge set.

A very important conclusion can be deduced from equation (2). On the right-hand side, M is proportional to thickness and is being divided by rigidity, I, which is proportional to thickness cubed, see equation (1). Therefore one power of thickness cancels out. Hence:

Potential peening distortion, 1/R, is inversely proportional to the square of the component's thickness.

DISTORTION CONTROL

We must start by acknowledging that virtually every shot peening operation imposes some degree of distortion on a component. This distortion may be welcome as for Almen intensity measurement and for peen forming. On the other hand, if peening imposes an unacceptable level of distortion we must try to reduce it.

Available methods for reducing peening distortion are limited. Some that come to mind are as follows:

1. Reduce surface compressive force
This is the most obvious method—achieved by inducing a thinner deformed surface layer (by using smaller shot and/or peening intensity). The disadvantage is that the customer may insist that a specified thickness of deformed and compressed surface layer is required in order to optimise component performance.

2. Pre-machine component with reverse distortion
This is feasible if the peening distortion is very small (but still unacceptable) so that a tiny amount of pre-machining can be applied. Peening distortion then becomes peen-forming. The method would require that the peening distortion is highly reproducible and would rarely be recommended.

3. Post-peening machining
Some fine-finish machining operations could be postponed until after peening has been carried out—hence removing any distortion effect. This could be a useful technique.

4. Mild stress-relieving
Shot-peening improves service performance by a combination of surface work-hardening and a compressed surface layer. Mild stress-relieving would reduce the surface compression force without inducing a significant reduction of surface work-hardening.

5. Compressive strain peening
Tensile strain peening is a well-established process. Components such as railway wagon springs have the peening surface put into tension during peening. After peening the strain is removed, leaving higher levels of compressive stress in the peened surface. The opposite type of strain, compression, could be applied during shot peening. This would give a lower level of compressive stress in the peened surface, reducing distortion, but would preserve the depth of the work-hardened surface layer.

6. Modification of component design
This involves increasing component rigidity in regions affected by shot peening distortion.

DISCUSSION

This article, being an overview of distortion, has necessarily been superficial in many respects. Several of the contributory factors have been dealt with in much greater depth in previous articles in this series.

The spring model of residual force distribution is believed to be particularly useful for illustrating distortion generation.

For a given component, the most important factors controlling distortion are the compressive surface force generated by shot peening and the inherent rigidity of the component. It has been shown that the extent of distortion is inversely proportional to the square of the component's thickness. The potential for distortion of steel components can, for example, be predicted using the observed distortion of steel Almen strips (obtained during intensity measurements). For example, if the thickness of a rectangular component was ten times that of the Almen strip then component distortion, per 76 mm length, would be roughly one-hundredth of that measured for the strip.

Rigidity estimates can be used to explain the multiplication factors, 3.0 and 3.2, proposed for comparing intensity values derived from N, A and C strips.

The rigidity of complex component sections can be approximated by using the nearest textbook example. A mechanical engineer's specialised knowledge might, however, need to be employed.

Finally, we must accept that shot peening will inevitably induce distortion. Fortunately the degree of component distortion is usually insignificant. It may, however, be a required feature.