Analytical-Numerical Model to predict CRS created by Inner Shot Peening Applied on Small ID Tubes

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Abstract

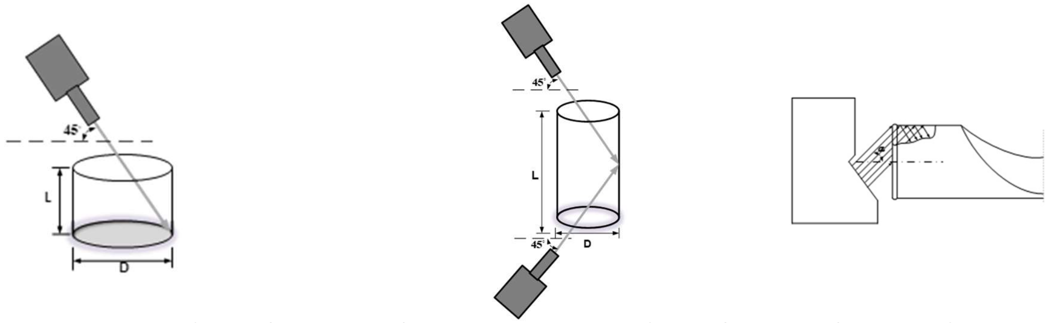
In this work as main aim, the process parameters of inner shot peening by air-blast process combined with special nozzles are analyzed. To guarantee a flow direction, diverting features are used to peen the inner surface of tubular small complex geometry elements with uniform results. The analytical relationships between them are developed and coupled to existing analytical compressive residual stress and Almen Intensity prediction models in order that, by numerical calculation, the resulting process profiles could be used in early stages of product/process development or for the improvement of currently running set-ups.

Keywords Surface treatment, tubular components, inner shot peening, analytical modelling, nozzles for inner shot peening, compressive residual stress profile, Almen intensity.

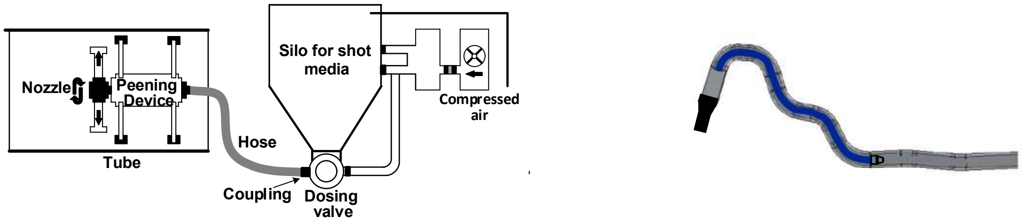
Introduction

The most recent trends in automotive, aerospace and biomedical product development involve aggressive part weight reduction targets. Therefore, a good and feasible strategy would be to apply the shot-peening process on the inner surface of tubular elements with the purpose to provide them, especially in critical zones or high stress zones, with improved compressive residual stresses, at these zones the wall thickness of tube can be then reduced by subtracting mass to the part, while preserving the same equivalent fatigue life performance or much better than solid elements that are only outer shot peened or than tubulars however not inner treated and with no wall thickness reduction. In [1] it is shown that internal shot blasting increases the life time from 127% in bars with a 48% decrease ratio between the weight and the inner radius of the bar, to 332% in those that have a 36% decrease ratio between the weight and the inner radius of the bar.

The inner shot peening indeed exists for non-complex shape tubes, however applied with blast from outside either into one end of a blind hole or to both ends of a passed hole depending on the L/D ratio or with wheel from outside of the hole, using the projection angle of the shot as shown in Figure 1 or by blasting from inside on the whole surface of straight tubes of large diameters where the peening device runs into the tube as show Figure 2. In [2] is claimed that by blasting, energy consumption is high with not always uniform results, in order to improve this, a method with a shot stream by wheel that with a pre-determined angle to middle point of length axis was there proposed.



a) Blasting to one end of tube L/D <1 b) Blasting to both ends of tube L/D>1 c) by wheel from outside
Figure 1. Inner shot peening from outside



a) By blasting inside a tube of large diameter b) By complex tubular bent bar peened at localized zones

Figure 2. Inner shot peening from inside

Nevertheless, the application of the inner shot peening is under study for very small diameter tubes and complex geometries, such as a tubular stabilizers or other small diameter bent ducts. Main difficulties are the length and thickness of the nozzle. that cannot be freely introduced and travel through the bends of the small diameter tube as well as the hose or lance that stuck or twists then making it hard to guarantee a full coverage-controlled peening of the inner surface of the tube. To improve the profile of compressive residual stresses several adaptations are proposed in the type of nozzle used in the internal blasting process.

The most feasible solution to inner-peen small diameter tubes is to use compressed air blasting. In a conventional process specifically with a straight nozzle, the flow direction of the compressed air and shot mixture inside the hose, and after the outlet of the nozzle well after a stable flow is achieved coincides with the axis of the tube. This means that the angle of impact of the particles against the inner surface of the tube would be very small, so the kinetic energy transferred to it would be as well low. So, if the flow direction of the compressed-air shot mixture is diverted somehow, the inner surface of the tube could be impacted with larger angles, let say with an angle close to 90°degrees.

Development.

There are multiple parameters that influence the results of a shot blasting process and therefore the generation of the compressive residual stress profile σ [3]: the dimension and hardness of the shot (HVs), the hardness of the workpiece (HV), the exposure time (t), the application pressure (P) and the speed of the shot at the moment of impact (v). The latter is very decisive, since its effect is related to the kinetic energy developed in the process and influences both the value of the maximum compressive residual stress that is reached as well as the depth (z) at which this maximum stress is given, as shown in Figure 3.

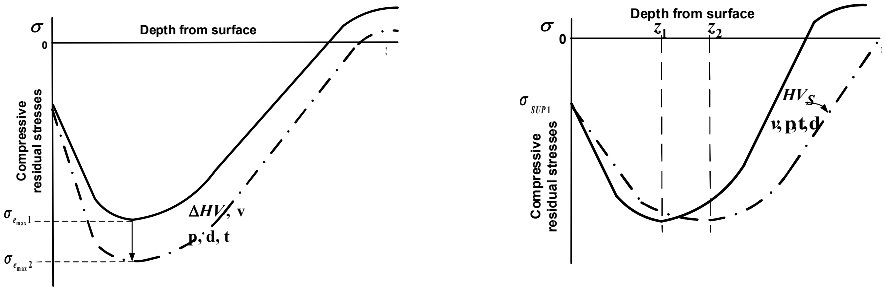


Figure 3 Influence of main process parameters on the residual stress profile.

Among all these process parameters, shot speed is also one of the more difficult parameters to measure, for the particular case of outer shot peening of parts, several methods have been proposed to estimate [4, 5] or measure their value [6], and once known it is possible to analytically perform [7, 8] or by means of numerical methods such as FEM analysis [9], a fairly approximate prediction of the compressive residual stress profile to be achieved. In the case of inner shot peening, once having an estimation of the shot speed, it may be possible to predict compressive residual stress too, so it is important to establish a mathematical relationship between the involved process parameters in order to calculate the shot speed.

A mathematical relationship, that describes the normal pressure acting on two elastic revolution bodies in the absence of friction is based on Hertz theory equation [10].

$$p(r) = p_0\left[1-(r / a_e)^2\right]^{1/2}, \quad a_e = \pi p_0 R / 2E_H \tag{1}$$

where $p(r)$ is pressure distribution along radial direction, r is radius from coordinates origin, p_0 is maximum pressure at r=0, a_e is contact radius, R is relative radius of the interphase R_1 (shot) / R_2 (work piece) and E_H is the equivalent Young's Module.

When it is considered that for the particular case of shot peening, the impact of the shot seen as developed kinetic energy converted into elastic work, the equations for determining maximum elastic pressure and maximum contact radius are transformed into:

$$p^* = \frac{1}{\pi}\left[40\pi k\rho E_0{}^4 (V\sin\theta)^2\right]^{\frac{1}{5}}, \quad a_e = 5/4[\pi k\rho(V\sin\theta)^2 / E_H]^{1/5}(D/2) \tag{2}$$

where Vsinθ is shot impact speed normal component and K is eficiency coefficient related with elastic and thermal dissipation.

The magnitude of the shot speed to introduce in the former equation for the specific inner shot peening process needs to be dynamically analyzed. The machine of the study is focused on fulfilling process capability, full coverage and consistent compressive residual stress profile, based on a compressed air shot peening machine. This machine consists of several systems that ensure the continuity of the shot flow when applying the process on the workpiece, which are shown in the diagram in figure 4. The inner diameter of the workpiece ranges from a minimum of 15 mm up to a but not limited of maximum 24 mm. Flexible lancers are pushed into the tubular work pieces with servo control of displacement and speed, of course possible to synchronize several lancers in order to maintain an acceptable production rate.

The total flow path of the working materials required for the treatment of the part, impeller (compressed air) and driven (shot) is shown in Figure 4. In it, three interfaces can be identified and their analysis is important to consider. As for the transport stage, there are only changes in the diameters of the conductive hoses in order to increase the speed of the mixture.

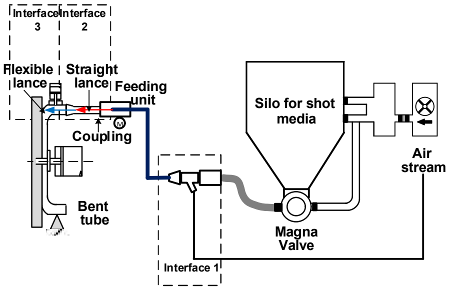


Figure 4 Diagram inner shot peening machine showing material streams and main interfaces.

At interface 1 "incorporation of shot-flow into compressed air stream", the speed of the impact particles (shot) incorporated into the jet is determined by the conservation of the mechanical Momentum, considering that the speed of the abrasive is zero before incorporation with the air flow and that the mixture of air and abrasive have the same speed after incorporation.
At the mixing point of shot and air, assuming momentum conservation, the equation is:

$$(V_{a/s})_2 = (V_a \dot{m}_a)_1 / (\dot{m}_a + \dot{m}_s)_2 \tag{3}$$

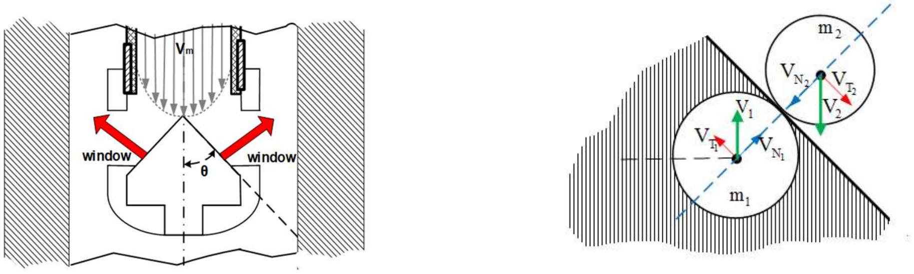
where $V_{a/s}$ is air/shot speed, V_a is air speed, $\dot{m}_a$ is mass flow air and $\dot{m}_s$ is mass flow shot.

For steady state and mass conservation at the hoses sections and not having a density change of the air/shot mix between any given point P1(inlet) and P2 (outlet):

$$(V_{a/s})_2 = V_{a/s\,1}(D_1 / D_2)^2 \tag{4}$$

where D_1 is Diameter inlet and D_2 is Diameter outlet.

Using a cone arrangement like shown in Figure 5 a) one can divert the air-shot flow to the inner surface of the work piece with a suitable angle to get better peening results.



a) Diverting Cone

b) Interaction single shot and cone at impact

Figure 5. Cone arrangement for proper peening direction and impact shot/cone

The impact speeds of a shot particle and the cone are denoted with N sub-index for the normal direction and with T sub-index for the tangential as is shown in Figure 5 b):

$$m_1V_{11} + m_2V_{21} = P \tag{5}$$

$$m_1V_{1N1} + m_2V_{2N1} = m_1V_{1N2} + m_2V_{2N2}, \qquad m_1V_{1T1} + m_2V_{2T1} = m_1V_{1T2} + m_2V_{2T2} \tag{6}$$

where P is the Momentum.

Assuming smooth surface of cone and double rounded shot, then with small surface roughness tangential speeds are negligible for the present study. Solving (5) and (6)

$$V_{1N2} = V_{1N1}(m_1 - m_2) + 2m_2V_{2N1} / (m_1 + m_2), V_{2N2} = V_{2N1}(m_2 - m_1) + 2m_1V_{1N1} / m_1 + m_2 \tag{7}$$

In order to consider a purely elastic impact, the restitution coefficient mainly ruled by material hardness as well as surface state of the impacting materials will be later assigned with value of 1.

$$\varepsilon = V_{rN2} / V_{rN1} = (V_{2N2} - V_{1N2}) / (V_{2N1} - V_{1N1}) \tag{8}$$

where sub-index r represent restitution

Due that speed of the lance and the attached nozzle with inner cone (m_1) is very small with regards to the shot speed (0.005 m/s/100 m/s), the cone is practically considered fixed in the system, then V_{1N1} y V_{1N2} are nearly zero, then $m_1 >> m_2$:

$$V_{2N1}\varepsilon = V_{2N2} \tag{9}$$

As shown in Figure 6 $V_{2N1} = V_{21}\sin\theta$ where θ is half the angle of the cone, then:

$$V_{2N2} = \varepsilon V_{21}\sin\theta \tag{10}$$

The particle’s normal speed component of the shot and cone impact determines the impact angle on the inner Surface of the tube. A perpendicular impact on the inner surface of the tubes means the higher amount of kinetic energy used to create the deeper and of higher magnitude compressive residual stresses.

$$V_{2N3} = V_{2N2}\cos\theta \tag{11}$$

Given that $V_{21} = V_2$ Equation (10) is rewritten as:

$$V_{2N3} = \varepsilon\, V_2 \sin\theta\cos\theta \tag{12}$$

Figure 7 shows speed factor $\sin\theta\cos\theta$ with angle variation of the nozzle´s cone. The factor is maximum at 90° angle.

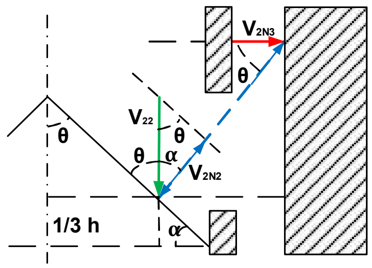


Figure 6. Components of V_2 at impact points 2 and 3

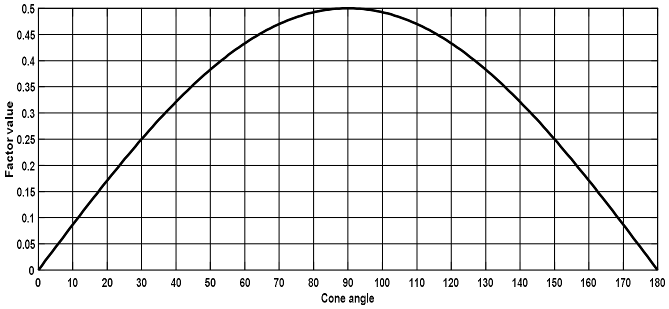


Figure 7. Speed factor $\sin\theta\ \cos\theta$

By Introducing the actual calculated speed V_{2N3} (12) impacting the work piece material at an angle of ca. 90º. Eq. (2) transforms in Eq. (3). Here V_{2N3} replaces V sinϴ because normal component is already considered.

The coupling of the modified Hertz equation (including the V derived for inner shot peening) with the analytical model proposed in [8], [11] in order that the compressive residual stress profile chart for inner shot peening can be predicted, was written in form of a numerical algorithm calculating this value each delta depth of 1 micron trough the thickness of an Almen type "N" strip.

Results

The inner shot peening process were applied, using the machine shown in Figure 4, in critical zones of a tubular element used in the automotive suspension, which has general dimensions of 1200 x 450 x 300 mm and Φ 32 x 5.1 wall thk. mm. Material is 34MnB5 quenched and tempered to Rm = 1650-1800 MPa. To provide fatigue life enhancement it is necessary to achieve an CRS profile with the following specifications in the mentioned zones: -450 MPa at 3 to 5 µm and -600 MPa at 10 to 20 µm.

Using the expression (12) coupled with existing mathematical models of shot peening process and by means of numerical calculation for different sets of input parameters, air Pressure (bar) and shot flow (kg/min), selected from DOE matrix with better output response, the CRS profiles by simulation were obtained, as shown in charts 8 and 9.

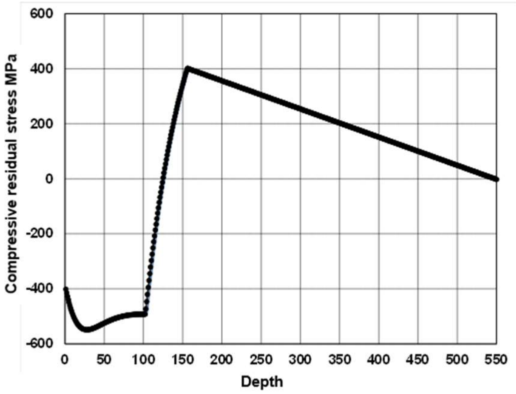


Figure 8 Simulation Param. Set 1
P= 6 bar, Shot flow=1400 kg/min

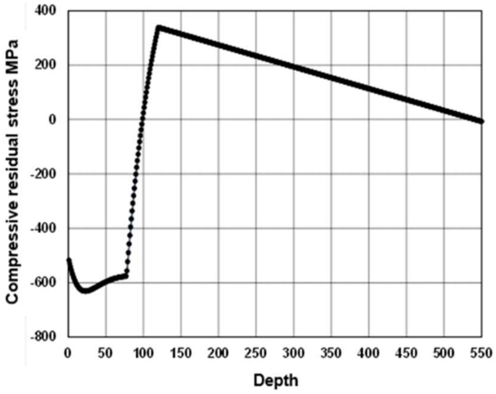


Figure 9 Simulation Param. Set 2
P=5 bar Shot flow=2000 kg/min

In order to verify the correspondence of the predicted results with actual measure values, tubular bars samples were processed with same parameter sets. CRS were measured on these samples by X-R diffractometer according to [12] as reference, at depths of 0, 5 and 20 µm. The results are shown in charts 10 and 11.

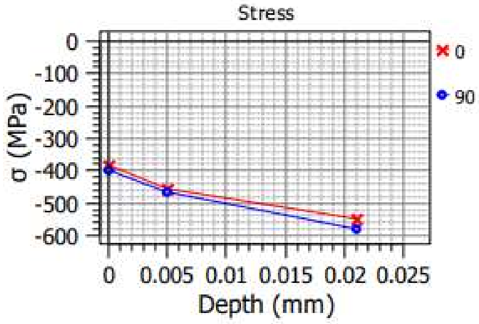


Figure 10 X-R Diffr. Meas. Set 1
P=6 bar, Shot flow=1400 kg/min

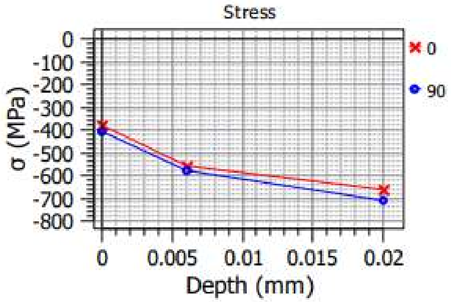


Figure 11 X-R Diffr. Meas. Set 2
P=5 bar, Shot flow=2000 kg/min

Observations and Conclusions.

As initially stated, it was possible to get good peening results on the inner surface of a small tube, when implementing nozzle with a diverting cone in order to profit as much as possible from the kinetic energy, targeting a c.a. 90° angle. This assumption was brought into the an already analytical/numerical proposed model, for peening an “A” Almen Strip peening to full coverage; however here changing to Almen “N” strip due to the range of peening intensity. The given specification of -450 MPa, to comply with the targeted Fatigue Life Cycles for the component of study was well achieved for both proposed parameter sets. Furthermore, is evident that the higher rate of shot mass flow effectively pushed the compressive residual stress profile deeper into the material.

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