OVERVIEW OF THE EFFECTS OF SURFACE ENHANCEMENT PROCESSES ON PLASTIC STRAIN, WORK HARDENING AND RESIDUAL STRESSES

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ABSTRACT

Compressive surface stresses are found to enhance the fatigue life of components, as fatigue cracks originate mostly from surfaces. From among the various surface enhancement processes, this review paper focuses on shot peening methods since they are the most complex in evaluating the material response due to the inherent stochastic nature of several variables. Peening can produce different amounts of near surface plastic deformation for the same residual stress and vice versa for different combinations of input parameters. Knowing the reasons why such variations occur will enhance the understanding of shot peening and other residual stress inducing processes. Many researchers have done experimental and theoretical studies to understand the underlying mechanisms of shot peening. This paper provides an overview of that extensive research and suggests some remaining tasks.

1. INTRODUCTION

Designing against fatigue degradation during service continues to be a challenge in many engineering applications.. To mitigate service loading and potential detrimental manufacturing operation residual tensile stress, residual compressive stress (RCS) is induced using various processes to shift the crack initiation location to a subsurface region (1). Currently we focus on the four Mechanical Surface Enhancement (MSE) processes, viz., Shot Peening (SP), Laser Shock Peening (LSP), Roller Burnishing/Low plasticity Burnishing (LPB), and Hole expansion (HE).

These processes help to avoid costly alternatives to increase fatigue life such as use of advanced materials or modified metal removal processes (2) while reducing the life-cycle cost of the processed parts. These processes also help resist corrosion and wear (2) (3). As aircraft engines use expensive metals and alloys (4), including the beneficial aspects of RCS in the design stage is always desired (5). Each process modifies the material microstructure and surface roughness differently (6). The induced RCS relaxes due to mechanical and thermal loads to different degrees (7). Over-exposure to surface enhancement processes as in shot peening can result in detrimental effects as well (8). Thus it is important to understand the factors that influence the mechanics of the above mentioned processes to optimize the mechanical responses. The paper summarizes the available literature relating to theoretical studies on the above MSE processes and the influencing parameters

2. METHODS FOR STUDYING RESIDUAL STRESSES

Both experimental and theoretical studies are necessary to understand and simulate a process.

2.1. Experimental Methods

Several measurement techniques exist to measure residual stresses and it becomes important to measure non-destructively if possible (9). Withers (10) discusses methods to measure three levels (Type I, II and III) of residual stresses. The following methods are used extensively:

- Hole Drilling method (11)
- X-ray Diffraction (for type I and II residual stresses) (12)
- Neutron Diffraction (13)

2.2. Theoretical Methods

Most researchers use continuum mechanics based approaches for predicting residual stresses and associated plastic strains All four RSC stress inducing processes involve plasticity, fracture and contact mechanics. SP and LSP also involve shock waves and probabilistic phenomenon. Amongst the several available numerical methods Finite Element Method (FEM) is widely used. The LSP process simulation typically involves computation of shock wave propagation due to laser pulses while the SP process may require wave propagation due to impacts (14).

Both SP and LSP involve processes whose spatial and temporal scales are many orders greater than the area and time duration at which the stress wave is applied. This may necessitate employing multi-scale methods. In addition, a stronger, harder nano-crystalline structure (15) develops due to peening(16). The multi-scale methods used span the range from atomistic to single crystals to poly-crystals to micromechanical to macro models. Different techniques exist at different spatial levels that also have a bearing on the temporal scales.

3. MECHANISM

The four processes generate RCS along with cold work. In an optimum condition, the surface roughness should be as low as possible with the magnitude and depth of RCS as high as possible **(17)**.

3.1. Shot Peening

Shot peening is a controlled cold working process involving multiple and progressively repeated impacts. Many authors have covered the details of the peening process (18) (19) (20) (21) (22). More information can be found on different shot types and mechanisms of shot delivery (22). Three important specifications that cover peening are SAE J442/443, AMS2432 and MIL-S-13165C. Different types of shots are compared in (23). The shots must be at least as hard as the peened material. The fundamentals of SP are reviewed by Lieurade and Bignonnet (17) and the surface microstructural changes are covered in (7). The cold work topographies of typical materials are given in (17).

Generally, the fatigue life improvement depends on peening intensity and coverage. A detailed flowchart (17) provides a comprehensive list of parameters. Shot peening changes the following target material parameters:

Metallurgical: structure, hardness
Mechanical: residual stress magnitude and distribution, depth of plastic deformation
Geometrical: surface roughness

In the industry, Almen strip curvature is used as a measure of the intensity of peening. Almen strip material and dimensions are standardized by American Military Standards. However, the Almen system does not provide a measure of the target material surface deformation. Some key issues are:

- The same intensity can be produced with different combinations of shot sizes and velocities.
- For different material and/or hardness parts, fatigue lives may be different when the Almen intensities are the same.
- Small features and components cannot be peened using high Almen intensities.
- The inherent variation in the strips and gauges**(24)**
- The operator variability can lead to process variation during manual peening **(22)**.

Thus, the relationships between the peening parameters and actual part fatigue life capability remain complex and shot peening is still generally used only as an additional safety measure in many industries (17).

3.2. Laser Shock Peening

LSP has gained more importance as an industrial process very recently(25). An LSP overview is given in (26). LSP provides an alternative to SP offering deeper, potentially more stable, residual stress penetration. Micro-scale laser shock peening is also under study (27).

A high-energy laser beam when used for short time intervals produces residual compressive stress (28) (29). Typically a Nd:glass slab laser system is used with wave-front corrections to increase the throughput (30). The laser beam traverses first through a transparent medium (water or glass) and is absorbed by the opaque layer (black paint or aluminum foil). The opaque medium reaches plasma state locally and expands within the confines of the transparent medium, thus protecting the metal from thermal effects (31). This generates high pressure that travels through the metal generating an elastic-plastic stress wave (29). (32). This wave first creates a tensile stress field, which results in RCS when constrained by adjoining material. (33).

3.3. Low Pressure Burnishing

Roller Burnishing or Low-Pressure Burnishing (LPB) is a newer technique to produce residual compressive stress (4) (34). Altenberger gives an historical overview (18). A roller or ball is moved over the surface under pressure. Different types of burnishing exist viz., normal, vibratory (35) and ultrasonic. The burnishing produces a deep layer of compressive stress with less cold work than SP. It can improve surface finish (36). As with the other processes, the RCS increases from surface to some depth and then decreases to become tensile (37). The key parameters include force, speed, feed-rate, lubrication, ball material and diameter, work-piece material, pre-machined roughness and frequency of oscillation (38) as in Table.1. The relationships between different burnishing parameters have been discussed in (39).

3.4. Hole Expansion

The operation is of two types, split sleeve and split mandrel (40). The split mandrel operation can provide better fatigue strength than split sleeve operation. During the expansion of the hole, the stresses reach tensile yield. The surrounding elastic material drives to RCS as the mandrel is withdrawn. The key parameters affecting the work hardening and the compressive stresses (41) are given in Table.1. The effects of important mechanical modeling phenomenon are listed in Table.2. It can be seen that more parameters are important in shot peening mechanics than the other three processes. Response factors of the four MSE processes are provided in Table.3. Shot peening produces relatively higher surface roughness and cold work compared to the other three methods RCS magnitude and depth are lower.

4. THEORETICAL STUDIES

4.1. Shot Peening

Empirical: Shen and Atluri have evolved an analytical solution that considers shot velocity **(42)**. Using the Hertzian contact and elastic-plastic theories, simplified formulae have been developed to predict the stress field **(43)**. DeLitizia has come up with a cubicexpression of stress versus depth **(2)**. Al-Hassani has provided an overview of various aspects of the mechanics through analytical solution **(22)**. Watanabe et al analytically evaluate RCS as a superposition of stresses. The nominal fatigue strength is determined based on the analytical expressions for the residual stress and internal fatigue strength **(23)**. The elastic RCS is calculated as the sum of stresses due to forces and temperatures **(24)**. An equivalent static load that produces the same strain pattern as that of multiple shots has been used alternately **(44)**. Iida has calculated dent diameter as a function of peening parameters **(2)**. Guechichi and Castex conclude that the cold work can have a more beneficial effect than RCS due to SP **(18)**. Al-Obaid **(45)** has attempted to provide theoretical expressions for single-shot impact by assuming the peening to be quasi-static and compared with experimental results.

FEM: The magnitude of the RCS depends on factors such as material, hardness, size and velocity of the shot (46). In this work by Levers et al, pre-stress effects have been created using temperature loads to avoid the complexity of modeling multiple impacts. This has been extended by Gardiner to simulate peen forming (24). Planes parallel to the surface have been applied with eigen strains to impart the pre-stress conditions (47). This method has been found to match the cold work calculated through other analytical methods (18). As Almen intensity continues to be the measure of peening process, Guagliano has come up with a process of relating it to FEM results (48). The multi-shot impingement produces more RCS than the single-shot impingement, while the plastic strain remains the same (49). Hassani has used ABAQUS to calculate stresses with strain-rate non-linear work hardening effects to compare with his theoretical results (24). Guagliano et al have combined FEM and a set of non-dimensional parameters to relate the peening parameters and the stresses (24).

Webster (50) has found that high cyclic plastic strains can also wipe out the fatigue strength improvement in a shot peened part. Han et al.(51), have calculated the residual stress distribution due to a simulated multi-impact and applied the results on a test specimen so that stresses due to service loads can be superimposed. Meo and Vignjevic (52) have analyzed the residual stress development in welded structures due to shot peening using a transient method to account for elastic and plastic waves, inertia and strain rate effects. Deslaef et al. (53) have simulated coverage rate and shot speed variations by FEM. It is shown that the stress field created by impacts of the first set of shots is made inhomogeneous by subsequent impacts (54). When multi-shot impacts occur, residual stresses prevent further plastic flow and after a few cycles the entire deformation will be elastic (55).

DEM: Han and Peric (56) have performed a two-dimensional analysis treating the peening balls as rigid circles. The work has been extended with three-dimensional laws by the same authors (57). They have also simulated multi-impact and found that single-impact results are significantly different from multi-impact results. The above studies using discrete element methods may enable modeling the effects of shots made from different materials and hardness.

Multiscale Models: Peric and Han have supported strongly the case for multiscale modeling due to the very small shot size when compared to the size of the component. SP modifies the material substructure at the surface (18) and this determines the RCS distribution and fatigue strength (23). Nano-crystals form at the surface of the shot-peened component by Surface Mechanical Attrition Treatment (SMAT) with multi-directional loading (18) due to dislocation formation, movement and annihilation. Xinling et al (58) has developed a method of using dislocation dynamics to evaluate plastic strains due to shot peening. The formation of nano-layer occurring with smaller shots is a function of contact duration and strain-rate (59).

Material Models: An elastic-plastic material model with strain rates, damping and deformable shot is considered to predict the stress field due to SP (60). Fathallah has used the material model by Guechichi and Khabou to consider the effects of friction, inclined impact and hardness ratio (61) (62). Frija et al. have used a combined damage model of Chabache and Lemaitre for Waspalloy (63). Lillamnad et al. also use the Chabache model for engine disk components (64). Al-Hassani has proposed that shakedown, reverse yielding, Bauschinger effects and strain-rate play a role in the accurate prediction of RCS (65). Slim et al. use the elastic-plastic method proposed by Zarka and Inglebert to calculate RCS (66). The theoretical RCS distribution over depth was found to well match experiments (67). The effect of temperature rise due to SP is coupled with mechanical effects through a thermo-elastic plastic model (18).

Stochastics: In shot peening, even the measurement parameters are stochastic in nature. For example, the coverage is assumed to follow a normal distribution below the nozzle (55). By tightly controlling the tolerances of these variables, a statistical minimum intensity can be assured. The impact pattern development follows a Poisson distribution and coverage evolves accordingly from multiple impacts (62). Some of the variables are more discretely controllable and a robust design method has been proposed (62). Using a Monte-Carlo method, the surface topography can be simulated and found to match well with experiments (17). (7).

4.2 Laser Shock Peening

Empirical: Chen et al. (68) have evolved an empirical formula to calculate RCS due to LSP. Among the numerical methods, 3D FEM is used for analyzing LSP (69).

FEM: FEM using explicit dynamics has been employed to predict single and multiple shots (70). A finite difference method code (for wave propagation) has been coupled with FEM (to predict stresses and strains) at each time step (71). Braisted and Brockman (72) have analyzed the LSP effects on titanium and steel alloys using an axis-symmetric model in ABAQUS. The work has focused on developing a constitutive law to include very high strain-rate and single impact. A two step process with an explicit step for shock propagation and implicit step for relaxation is evolved for LSP and LPB (73). The LPB has been analyzed using ABAQUS (74) and produced compressive stresses at the surfaces and tensile stresses at the center (75). Multiple LSP impacts produce deeper RCS than single impact and by adjusting the locations of these impacts increased RCS can be obtained (76). The material phase transformation and thermal field have also been considered in the LSP simulation of stresses (77). Dual-sided application of LSP on thin sections prevents excessive deformation and spalling (78). The measured RCS from LSP is applied as strain in an elastic medium to the FE model (79). This is accomplished through a variational approach to convert the strain distribution to eigen-strains (80). Wu and Shin have employed three sub-models, viz., breakdown-plasma model, confined-plasma model and FEM (81). Massively parallel FE simulations of LSP have been attempted by Warren et al (82).

Multiscale: Multiscale approaches have been employed in analyzing LSP (83). The micro and mesoscale simulations of manufacturing processes including LSP are given in (84).

4.3. Low Plasticity Burnishing

Empirical: Mathematical modeling of burnishing has gained importance recently (85). Analytical expressions have been developed that include the deformation of wedge-like asperities due to burnishing (86).

FEM: FEM remains the key numerical technique (87) with elastic-plastic modeling (88). Martin has used kinematic and isotropic hardening in various models to apply the pressure loads incrementally (89). A mixed hardening rule has been employed in an axisymmetric analysis (90). Cyclic material stress/strain data has been used in a 3D FE model and the results match well with test results (91). Incremental elastic-plastic strain with a Lagrangian formulation is used for numerical simulation of burnishing (92). Black et al. have used slip-line theory to calculate the plastic strains and plasticized depth (93). Smelyanskii (94) has proposed analytical solutions of the relations between shear strain and plastic deformation. A good correlation is found between analytically predicted roughness and feed (95). Lin et al. (96) have evolved a burnishing factor using tribology and determined a quadric relation with surface roughness. High burnishing pressure provides better surface finish and higher RCS (97). Another study involving 3D thermo-mechanical coupled analysis also brings out that larger force along with smaller feed and ball diameter result in higher RCS and depth (98). An elastic-plastic FE model has been used to calculate the deformation and residual stresses (99). A 3D analysis to simulate the residual stresses in a crankshaft fillet region has resulted in good correlation with tests (100). The three components of the burnishing force are found to exponentially increase with desired depth (101).

4.4. Hole Expansion

Empirical: Wang (102) has derived a closed form solution with Bauschinger effect and Ramberg-Osgood hardening. Ball has extended Hsu and Forman's solution to include elastic-plastic unloading (103). An analytical model with plane stress conditions is used to conduct a parametric study of the bauschinger effect, plate size, strain-hardening exponent etc (104).

FEM: To simulate a three step process i.e.. hole expansion, elastic recovery and finish reaming, FEM is employed by Kang et al (105) using ABAQUS for two aluminum alloys. Maximov et al. (106) have simulated cracks using a 2D FE model. Papanikos also has used an elasto-plastic 2D FE model to study two adjacent holes under cold working (107). 2D simulations with plane stress, plane strain and axisymmetric assumptions have implicated the need for using 3D analysis (108). The authors have extended the study to 3D analysis and found that the residual stress distribution in the vicinity of the machined surface is different from 2D analyses (109). Sequential expansion of adjacent holes reduces the RCS significantly (110). A combined penalty-Lagrange method has been used in ANSYS to model the contacts between mandrel and the holes in elasto-plastic analysis (111). LS/DYNA has been used to predict the RCS for the special process with a residual stress inducing indenter applied before drilling transverse holes (112). Rapid Prototyping is combined with LS/DYNA to predict the behavior of cold working of holes (113).

5. COMPARISONS

Altenberger (7) compares SP with other methods from a material perspective. The MSE processes develop different levels of cold work on the surface and high dislocation densities that result in plastic strains (114). LSP has produced the same level of RCS but decreased intensity of plastic strain compared to SP (115). LSP and a SP-LSP combination provide better fatigue strengths in comparison with just SP alone (116). LSP is able to provide better surface finish along with higher and deeper RCS than SP (117). Thus LSP is likely to replace other conventional processes (23). In mild steel, the LSP has caused 80% increase in hardness due to dislocation density increase, but the RCS level is higher in SP (118). High intensity peening followed by low intensity peening and mechanical polishing can produce fatigue strength as high as LSP (7). Rankin et al. found that the SP and LSP have the same RCS to 0.1 mm depth, but the depth of RCS is higher in LSP (119). In spring steel, deep rolling has produced higher and deeper RCS than stress peening (7). . The Ti-6Al-4V alloy has developed lower near-surface RCS and work hardening with SP compared to LPB, but the worked layer is thicker and the surface roughness is more. Lower deformation rate brings fatigue strength benefit in LPB in titanium alloy while polishing has shown improvement after SP. Zhang et al also conclude that RB is better than SP for fatigue strength at optimum conditions (120). Surface roughness and RCS play significant roles in fretting failure (121) and lubricants reduce the RCS magnitude.

6. CURRENT STUDIES AND FUTURE TRENDS

As mentioned in (122), FEM and knowledge integration form the basis of much of this multi-disciplinary work. An information-based approach can be used to analyze the complex shot peening process (18). The authors feel that this may lead to recognition that adaptive meshing techniques and meshless methods can prove to be more versatile in simulating surface effects. Nonlinear optimization techniques using Latin Hypercube methods can provide better optimized values. All four MSE processes have dislocation dynamics as the underlying mechanism suggesting that multi-scale simulations, that take grain-level interactions with dislocation dynamics into account, will provide more insight in the development of residual stresses and cold work.

Sl. No	**Shot Peening**	**Laser Shock Peening**	**Roller Burnishing**	**Hole Expansion**
1	Shot veleocity	Laser Power density	Ball Diameter	Tool Material
2	Shot Diameter	Repetitions	Ball Material	Hole Material
3	Shot Material	Target material	Force	Force
4	Target Material		Feed rate	
5	Angle of Impact		Speed of Ball	
6	Number of shots		Target Material	
7	Coverage		Lubrication	
8	Intensity			

Table.1. Key Parameters in the four MSE processes

Modeling Phenomenon	Shot Peening	Laser Shock Peening	Roller Burnishing	Hole Expansion
Plasticity	High	High	High	High
Contact mechanics	High	Low	High	Medium
Friction effects	High	Low	High	Low
Strain rate effects	High	High	Low	Low

Statistical effects	High	Medium	Low	Low
Thermal Effects	Medium	High	Medium	Medium/Low
Strainhardening/softening	High	High	High	High
Bauschinger Effect	High	High	High	High

Table.2. Relative Importance of Different Phenomenon in simulation of the MSE processes

	Shot Peening	Laser Shock Peening	Low Plasticity Burnishing	Hole Expansion
Surface RCS	Low	Medium	High	Medium
Max. RCS	Low	Medium	High	Medium
Depth of Max. RCS	Low	Medium	High	Medium
Cold Work	High	Medium	Low	Medium
Surface Roughness	High	Medium	Low	Low

Table.3 Response Parameters for the four MSE Processes

REFERENCES:

1 . Gabb TP, Telesman J, Kantzos P, Preve´y PS. Surface Enhancement of Metallic Materials. Advanced Materials and Processes. 2002 ;160(1):69-72.
2 . Fuchs, H.O. Proceedings of International Conference on Shot Peening-2. In: Proceedings of ICSP-2. Chicago, USA: 1984.
3 . Zhuang W, Wicks B. Mechanical Surface Treatment Technologies for Gas Turbine Engine Components. Journal of Engineering for Gas Turbines and Power. 2003 ;125(4):1021-1025.
4 . Bozdana AT. On the Mechanical Surface Enhancement Techniques in Aerospace Industry - a Review of Technology. Aircraft Engineering and Aerospace Technology. 2005 ;77(4):279-292.
5 . John R, Larsen, J, Buchanan D, Ashbough N. Incorporating Residual Stresses in Life Prediction of Turbine Engine Components. In: Proceedings of the 8th International Fatigue Congress. Stockholm: 2002. p. 1063-1070.
6 . Flavenot J. Residual Stresses Due to Mechanical Surface Treatment. Revue de Metallurgie. Cahiers D'Informations Techniques. 1997 ;94(2):188-197.
7 . Wagner L. Proceedings of International Conference on Shot Peening-8. In: Proceedings of ICSP-8. Garmisch-Partenkirchen, Germany : 2002.
8 . Domas P. Elevated Temperature Component Fatigue Robustness – An Holistic Approach. In: AGARD Conference Proceedings . 1995.
9 . Matzkanin GA, Yolken HT. A Review of Techniques for Nondestructively Characterizing Residual Stress in Metals. American Society of Mechanical Engineers, Pressure Vessels and Piping Division (Publication) PVP. 2000 ;4291-6.
10 . Withers PJ, Bhadeshia HKDH. Residual Stress Part 1 - Measurement Techniques. Materials Science and Technology. 2001 ;17(4):355-365.
11 . Lord J. Hole Drilling Techniques [Internet]. 2000 Sep 12;Available from: www.npl.co.uk/materials/residualstress/pdf_files/hole_drilling.pdf
12 . Noyan IC, Cohen J. Residual Stress Measurement by Diffraction and Interpretation. Springer-Verlog New York Inc.; 1987.
13 . Webster G, Wempory R. Non-Destructive Measurement of Residual Stress by Neutron Diffraction. Journal of Materials Processing Technology. 2001 ;117395-399.
14 . Laursen T. Computational Contact and Impact mechanics. Springer-Verlog berlin Heidelberg; 2003.
15 . Koch CC, Youssef KM, Scattergood RO, Murty KL. Breakthroughs in Optimization of Mechanical Properties of Nanostructured Metals and Alloys. Advanced Engineering Materials. 2005 ;7(9):787-794.
16 . Todaka Y, Umemoto M, Tsuchiya K. Comparison of Nanocrystalline Surface Layer in Steels Formed by Air Blast and Ultrasonic Shot Peening. Materials Transactions. 2004 ;45(2):376-379.
17 . Wohlfahrt H, Kopp. R, Vohringer O. Proceedings of International Conference on Shot Peening-3. In: Proceedings of ICSP-3. Garmisch-Partenkirchen, Germany: 1987.

18 . Schulze V, Niku-Lari A. Proceedings of International Conference on Shot Peening-9. In: ICSP-9. Marne la Vallée, France: 2002.

19 . Tufft M. Development of a Fracture Mechanics/Threshold Behavior Model to assess the Effects of Competing mechanisms induced by Shot Peening on the Cyclic Life ofa Nickel Based Superalloy, Rene-88DT. 1997 ;

20 . Kirk D. Shot peening. Aircraft Engineering and Aerospace Technology. 1999 ;71(4):349-361.

21 . Leghorn G. The Story of Shot Peening. A.S.N.E.Journal. 1957 ;

22 . Niku-Lari, A. Proceedings of International Conference on Shot Peening-1. In: Proceedings of ICSP-1. Paris, France: 1981.

23 . Iida K. Proceedings of International Conference on Shot Peening-4. In: Proceedings of ICSP-4. Tokyo, Japan: 1990.

24 . Nakonieczny A. Proceedings of International Conference on Shot Peening-7. In: Proceedings of ICSP-7. Warsaw, Poland: 1999.

25 . Clauer AH, Lahrman DF. Laser Shock Processing As a Surface Enhancement Process. Key Engineering Materials. 2001 ;197121-142.

26 . Montross CS, Wei T, Ye L, Clark G, Mai Y-. Laser Shock Processing and Its Effects on Microstructure and Properties of Metal Alloys: A Review. International Journal of Fatigue. 2002 ;24(10):1021-1036.

27 . Che H, Wang Y, Kyser J, Yao L. Advances in Microscale Laser Shock Peening
. Tsinghua Science and Technology. 2004 ;9(5):506-518.

28 . Masse J, Barreau G. Laser Generation of Stress Waves in Metal. Surface and Coatings Technology. 1995 ;70(2-3):231-234.

29 . Hill MR, DeWald AT, Demma AG, Hackel LA, Chen H-, Brent Dane C, et al. Laser Peening Technology. Advanced Materials and Processes. 2003 ;161(8):65-67.

30 . Dane CB, Hackel LA, Daly J, Harrison J. Shot Peening with Lasers. Advanced Materials and Processes. 1998 ;153(5):37-38.

31 . Rubio-Gonza´lez C, Gomez-Rosas G, Ocan˜a J, Molpeceres C, Banderas A, Porro J, et al. Effect of an Absorbent Overlay on the Residual Stress Field Induced by Laser Shock Processing on Aluminum Samples. Applied Surface Science. 2006 ;252(18):6201-6205.

32 . Watanabe K, Sano Y, Mukai N, Torikai H, Sasoh A. Influence of Metal Plate Thickness on Underwater Pressure Waves Induced by Laser Peening. Science and Technology of Energetic Materials. 2004 ;65(5):161-166.

33 . Fabro R. Laser Shock-hardening, Physics and Applications. In: Lasers and Electro-Optics . Europe: 1994. p. 6-6.

34 . Bohac D. Advances in Roller Burnishing. Automotive Industries AI. 1971 ;145(3):45-48, 59.

35 . Barski T. The Investigation of Operating Properities of the Surface after Hammering . In: ICSP-3. Garmisch-Partenkirchen, Germany : 1987. p. 179-182.

36 . Cantwell M. Mechanical Finishing: A Review and New Technologies. Products Finishing (Cincinnati). 2003 ;67(7):44-46.

37 . Fattouh M, El-Khaberry MM. Residual Stress Distribution in Burnishing Solution Treated and Aged 7075 Aluminum Alloy. International Journal of Machine Tools and Manufacture. 1989 ;29(1):153-160.

38 . Loh NH, Tam SC. Effects of Ball Burnishing Parameters on Surface Finish - a Literature Survey and Discussion. Precision Engineering. 1988 ;10(4):215-220.

39 . Murthy RL, Kotiveerachari B. Burnishing of Metallic Surfaces - A Review. Precision Engineering. 1981 ;3(3):172-179.

40 . Leon A. Benefits of Split Mandrel Coldworking. International Journal of Fatigue. 1998 ;20(1):1-8.

41 . Niku-Lari A. Shot-peening. In: ICSP-1. Paris: 1981. p. 1-21.

42 . Shen S, Atluri SN. An Analytical Model for Shot-peening Induced Residual Stresses. Computers, Materials and Continua. 2006 ;4(2):75-85.

43 . Ogawa K, Asano T. Theoretical Prediction of Residual Stress Induced by Shot Peening and Experimental Verification for Carburized Steel. Zairyo/Journal of the Society of Materials Science, Japan. 1999 ;48(12):1360-1366.

44 . Wang T, Platts M, Levers A. A Process Model for Shot Peen Forming. A.S.N.E.Journal. 2006 ;172159-162.

45 . Al-Obaid Y. Shot Peening Mechanics: Experimental and Theoretical Analysis. Mechanics of

Materials. 1995 ;19251-260.
46 . Levers A, Prior A. Finite Element Analysis of Shot Peening. Journal of Materials Processing Technology. 1998 ;80-81304-308.
47 . Korsunsky AM. On the Modelling of Residual Stresses Due to Surface Peening Using Eigenstrain Distributions. Journal of Strain Analysis for Engineering Design. 2005 ;40(8):817-824.
48 . Guagliano M. Relating Almen Intensity to Residual Stresses Induced by Shot Peening: A Numerical Approach. Journal of Materials Processing Technology. 2001 ;110(3):277-286.
49 . Li Y, Wang F, Lu J, Xu K. Finite Element Analysis for Shot-peening Models of Single Shot Impact and Multiple Impingement. Hsi-An Chiao Tung Ta Hsueh/Journal of Xi'an Jiaotong University. 2007 ;41(3):348-352.
50 . Webster GA, Ezeilo AN. Residual Stress Distributions and Their Influence on Fatigue Lifetimes. International Journal of Fatigue. 2001 ;23(SUPPL. 1):S375-S383.
51 . Han K, Owen D, Peric D. Combined Finite/Discrete Element and Explicit/Implicit Simulations of Peen Forming Processes. Engineering Computations. 2002 ;19(1):92-118.
52 . Meo M, Vignjevic R. Finite Element Analysis of Residual Stress Induced by Shot Peening Process. Advances in Engineering Software. 2003 ;34(9):569-575.
53 . Deslaef D, Rouhaud E, Rasouli-Yazdi S. 3D Finite Element Models of Shot Peening Processes. Materials Science Forum. 2000 ;347241-246.
54 . Helling CDG, Schiffner K. Numerical Simulation of Shot Peening. Computational and Experimental Methods . 2001 ;6303-311.
55 . Kirk D. Proceedings of International Conference on Shot Peening-5. In: Proceedings of ICSP-5. Oxford, UK: 1993.
56 . Han K, Peric D, Owens, D.R.J., Crook, A.J.L. A Combined Finite/discrete Element Simulation of Shot Peening Processes Part I- Study of 2d Interaction Laws. Engineering Computations. 2000 ;17(5):593-619.
57 . Han K, Peric D. A Combined Finite/discrete Element Simulation of Shot Peening Processes Part II- 3D Interaction Laws. Engineering Computations. 2000 ;17(5):680-702.
58 . Xinling M, Wei W, Wei Y. Simulation for Surface Self-nanocrystallization under Shot-Peening. Acta Mechanica Sinica. 2003 ;19(2):172-180.
59 . Liu JL, Umemoto M, Todaka Y, Tsuchiya K. Formation of a Nanocrystalline Surface Layer on Steels by Air Blast Shot Peening. Journal of Materials Science. 2007 ;42(18):7716-7720.
60 . Eltobgy MS, Ng E, Elbestawi MA. Three-dimensional Elastoplastic Finite Element Model for Residual Stresses in the Shot Peening Process. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture. 2004 ;218(11):1471-1481.
61 . Fathallah R, Inglebert G, Castex L. Prediction of Plastic Deformation and Residual Stresses Induced in Metallic Parts by Shot Peening. Materials Science and Technology. 1998 ;14(7):631-639.
62 . Champaigne J. Proceedings of International Conference on Shot Peening-6. In: Proceedings of ICSP-6. California, USA: 1996.
63 . Frija M, Hassine T, Fathallah R, Bouraoui C, Dogui A. Finite Element Modelling of Shot Peening Process: Prediction of the Compressive Residual Stresses, the Plastic Deformations and the Surface Integrity. Materials Science and Engineering A. 2006 ;426(1-2):173-180.
64 . Lillamand I, Barrallier L, Lalanne B, Castex L. Cyclic Modelling of the Mechanical State Produced by Shot-peening. Fatigue and Fracture of Engineering Materials and Structures. 2001 ;24(2):93-104.
65 . Al-Hassani STS. Shot Peening of Metals- Mechanics and Structures. In: Shot Peening for Advanced Aerospace Design. Anaheim California : 1982. p. 1-13.
66 . Slim S, Harm T, Inglebert G, Point N. Prediction of Residual Stresses Due to Shot Peening Using Modelling of the Material Behavior. Materials and Manufacturing Processes. 1995 ;10(3):579-588.
67 . Guechichi H, Castex L, Frelat J, Inglebert G. Predicting Residual Stresses due to Shot Peening. In: Proceedings of the 10th Conference on Shot Peening (CETIM-ITI). Senlis, France: 1986. p. 23-34.
68 . Chen R-, Hua Y-, Cai L. Estimate of Residual Stress of Steel Materials Induced by Laser Shock Wave. Zhongguo Jiguang/Chinese Journal of Lasers. 2006 ;33(2):278-282.
69 . Hu Y, Yao Z, Hu J. 3D FEM Simulation of Laser Shock Processing. Surface and Coatings Technology. 2006 ;201(3-4):1426-1435.
70 . Hu Y-, Yao Z-, Hu J. Numerical Simulation of Residual Stress Field for Laser Shock Processing.

Zhongguo Jiguang/Chinese Journal of Lasers. 2006 ;33(6):846-851.
71 . Arif A. Numerical Prediction of Plastic Deformation and Residual Stresses induced by Laser Shock Processing. Journal of Materials Processing Technology . 2003 ;136120-138.
72 . Braisted W, Brockman R. Finite Element Simulation of Laser Shock Peening. International Journal of Fatigue. 1999 ;21(7):719-724.
73 . Fan Y, Wang Y, Vukelic S, Yao YL. Wave-solid Interactions in Shock Induced Deformation Processes. In: 24th International Congress on Applications of Lasers and Electro-Optics, , ICALEO 2005 - Congress Proceedings . 2005. p. 479-488.
74 . Du J-, Zhou J-, Yang C-, Zhang X-, Ni M-, Cao X-. Numerical Simulation of Laser Peen Forming Based on ABAQUS. Zhongguo Jiguang/Chinese Journal of Lasers. 2006 ;33(SUPPL.):419-422.
75 . Zhou J-, Ni M-, Zhang Y-, Yang G-, Du J-, Cao X-. Theoretical Investigation and Finite Element Simulation of Laser Peen Forming of Metal Plate. Zhongguo Jiguang/Chinese Journal of Lasers. 2007 ;34(2):288-294.
76 . Ding K, Ye L. Simulation of Multiple Laser Shock Peening of a 35cd4 Steel Alloy. Journal of Materials Processing Technology. 2006 ;178(1-3):162-169.
77 . Bokota A, Iskierka S. Numerical Simulation of Transient and Residual Stresses Caused by Laser Hardening of Slender Elements. Computational Materials Science. 1997 ;7(4):366-376.
78 . Fan Y, Wang Y, Vukelic S, Yao YL. Numerical Investigation of Opposing Dual Sided Microscale Laser Shock Peening. Journal of Manufacturing Science and Engineering, Transactions of the ASME. 2007 ;129(2):256-264.
79 . Dewald AT, Hill MR. Model for Predicting Laser Peening Residual Stresses in Arbitrary 3d Bodies. American Society of Mechanical Engineers, Pressure Vessels and Piping Division (Publication) PVP . 2005 ;7209-214.
80 . Korsunsky AM, Regino GM, Latham D, Liu J, Nowell D, Walsh M. Eigenstrain Analysis of Synchrotron X-ray Diffraction Measurement of Residual Strains in Machined Nickel Alloy Plates. Journal of Strain Analysis for Engineering Design. 2006 ;41(5):381-395.
81 . Wu B, Shin YC. From Incident Laser Pulse to Residual Stress: A Complete and Self-closed Model for Laser Shock Peening. 2006.
82 . Warren AW, Guo YB, Chen SC. Massive Parallel Laser Shock Peening: Simulation, Verification, and Analysis. 2005. p. 287-295.
83 . Cheng G, Shehadeh M. Dislocation Behavior in Silicon Crystal Induced by Laser Shock Peening: A Multiscale Simulation Approach. Scripta Materialia. 2005 ;531013-1018.
84 . Williams RE, Melkote S, Sun W, Huang Y, Kinsey B, Yao D. Recent Advances in Micro/meso-scale Manufacturing Processes. 2005. p. 863-884.
85 . Nee AYC, Venkatesh VC. Mathematical Analysis of the Ball-Burnishing Process. In: CIRP Annals - Manufacturing Technology. 1983. p. 201-204.
86 . Korzynski M. Modeling and Experimental Validation of the Force-surface Roughness Relation for Smoothing Burnishing with a Spherical Tool. International Journal of Machine Tools and Manufacture. 2007 ;47(12-13):1956-1964.
87 . Nicoletti N, Aubry E, Fendeleur D, Renner M. A Finite Element Model for the Analysis of Roll Burnishing. Holz als Roh - und Werkstoff. 1997 ;55(3):183-187.
88 . Mader S, Klocke F. Fundamentals of the Deep Rolling of Compressor Blades for Turbo Aircraft Engines. In: ICSP-9. Paris, France: 2005.
89 . Martin J. Roller Burnishing - a Cold Working Tool to Reduce Weld Induced Residual Stress. ASME:Pressure Vessels and Piping DIvision. 2002 ;441115-122.
90 . Starzyn´ski G, Kucharski S. Simulation of Evolution of the Residual Stress in the Surface Layer Under Tension and Torsion. Materials Science Forum. 2002 ;404-407227-232.
91 . Zhuang W, Wicks B. Multipass Low-plasticity Burnishing Induced Residual Stresses: Three-dimensional Elastic-plastic Finite Element Modelling. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science. 2004 ;218(6):663-668.
92 . Kukielka L. Mathematical Modelling and Numerical Simulation of Non-linear Deformation of the Asperity in the Burnishing Cold Rolling Operation. Computational and Experimental Methods. 2001 ;5317-326.
93 . Black AJ, Kopalinsky EM, Oxley PLB. Analysis and Experimental Investigation of a Simplified Burnishing Process. International Journal of Mechanical Sciences. 1997 ;39(6):629-641.

94 . Smelyanskii VM. Mechanics of Strengtheneing the Surface Layer of Machine Parts by PSD Treatment. Soviet engineering research. 1982 ;2(11):19-22.
95 . Bouzid W, Tsoumarev O, Sai¨ K. An investigation of surface roughness of burnished AISI 1042 steel. International Journal of Advanced Manufacturing Technology. 2004 ;24(1-2):120-125.
96 . Lin YC, Wang SW, Lai H-. The Relationship Between Surface Roughness and Burnishing Factor in the Burnishing Process. International Journal of Advanced Manufacturing Technology. 2004 ;23(9-10):666-671.
97 . Sartkulvanich P, Altan T, Jasso, F., Rodrigues, C. Finite Element Modeling of Hard Roller Burnishing: An Analysis on the Effects of Process Parameters Upon Surface Finish and Residual Stresses. Journal of Manufacturing Science and Engineering, Transactions of the ASME. 2007 ;129(4):705-716.
98 . Deng WJ, Xia W, Zhou ZY, Chen WP, Li YY. Finite Element Analysis of Effects of Ball Burnishing Parameters on Residual Stresses. Materials Science Forum. 2004 ;471-472658-662.
99 . Bouzid Sai W, Sai K. Finite Element Modeling of Burnishing of Aisi 1042 Steel. International Journal of Advanced Manufacturing Technology. 2005 ;25(5-6):460-465.
100 . Courtin S, Henaff-Gardin C, Bezine G. Finite Element Simulation of Roller Burnishing in Crankshafts. In: Surface Treatment VI. Crete, Greece: 2003. p. 333-342.
101 . Luo H, Liu J, Wang L, Zhong Q. Investigation of the Burnishing Force During the Burnishing Process with a Cylindrical Surfaced Tool. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture. 2006 ;220(6):893-904.
102 . Wang G. An Elastic-Plastic Solution for a Normally Loaded Center Hole in a Finite Circular Body. International Journal of Pressure Vessels and Piping. 1988 ;33269-284.
103 . Ball D. Elastic-Plastic Stress Analysis of Cold Expanded fastener Holes . Fatigue and Fracture of Engineering Materials and Structures. 1995 ;18(1):47-63.
104 . Zhang Y, Fitzpatrick M, L. Edwards. Analysis of the Residual Stress around a Cold-expanded Fastener Hole in a Finite Plate. Strain. 2005 ;4159-70.
105 . Kang J, Johnson W, Clark DA. Three-Dimensional Finite Element Analysis of the Cold expansion of fastener Holes in Two Aluminium alloys. Journal of Engineering Materials and Technology, Transactions of the ASME. 2002 ;124140-145.
106 . Maximov JT. A Finite Element Simulation of the Spherical Mandrelling Process of Holes with Cracks. Journal of Materials Processing Technology. 2006 ;171459-466.
107 . Papanikos P, Meguid SA. Elasto-plastic Finite-element Analysis of the Cold Expansion of Adjacent Fastener Holes. Journal of Materials Processing Technology. 1999 ;92-93424-428.
108 . Poussard C, Pavier MJ, Simth D. Analytical and Finite Element Predictions of Residual Stresses in Cold Worked Fastener Holes. Journal of Strain Analysis. 1995 ;30(4):291-304.
109 . Korsunsky AM, Regino GM, Latham DP, Li HY, Walsh MJ. Residual Stresses in Rolled and Machined Nickel Alloy Plates: Synchrotron X-ray Diffraction Measurement and Three-dimensional Eigenstrain Analysis. Journal of Strain Analysis for Engineering Design. 2007 ;42(1):1-12.
110 . Papanikos P, Meguid SA. Three-Dimesnional Finite Element Analysis of Cold Expansion of Adjacent Holes. International Journal of Mechanical Science. 1998 ;40(10):1019-1028.
111 . Meguid SA, Papanikos P, Stranart JC. Residual Stresses in Aircraft Components: Part I - Nonlinear Finite Element Modelling. Proceedings of SPIE - The International Society for Optical Engineering. 1999 ;3586256-260.
112 . Flinn BD, Wiegman ME, Sigelmann M, Nam T, Easterbrook E, Mines A. Stress Wave™ Fatigue Life Improvement of 6Al-4V Titanium for Medical Implants. 2003. p. 220-225.
113 . Lu Y-. Integration of RP and explicit dynamic FEM for the visualization of the sheet metal forming process. International Journal of Advanced Manufacturing Technology. 2006 ;28(3-4):255-261.
114 . Wagner L. Mechanical Surface Treatments on Titanium, Aluminum and Magnesium Alloys. Materials Science and Engineering A. 1999 ;263210-216.
115 . Shikun S, Ziwen C. Laser Shock Processing of Titanium Alloy. In: International Technology and Innovation Conference 2006 (ITIC 2006). 2006. p. 1749-1752.
116 . Rodopoulos CA, Romero JS, Curtis SA, De los Rios ER, Peyre P. Effect of Controlled Shot Peening and Laser Shock Peening on the Fatigue Performance of 2024-T351 Aluminum Alloy. Journal of Materials Engineering and Performance. 2003 ;12(4):414-419.
117 . Du J-, Zhou J-, Yang C-, Ni M-, Cao X-, Huang S. Simulation Study on Stress Field After Laser-

peening and Shot-peening of Sheet Metal. Zhongguo Jiguang/Chinese Journal of Lasers. 2007 ;34(SUPPL.):98-101.
118 . J.P. Chu, J.M. Rigsbee , G. Banas, H.E. Elsayed-Ali. Laser-shock Processing Effects on Surface Microstructure and Mechanical Properties of Low Carbon Steel. Materials Science and Engineering A. 1999 ;260260-268.
119 . Rankin JE, Hill MR, Halpin J, Chen H-, Hackel LA, Harris F. The Effects of Process Variations on Residual Stress Induced by Laser Peening. Materials Science Forum. 2002 ;404-40795-100.
120 . Zhang P, Lindemann J. Effect of Roller Burnishing on the High Cycle Fatigue Performance of the High-strength Wrought Magnesium Alloy Az80. Scripta Materialia. 2005 ;52(10):1011-1015.
121 . Liu D, Zhang B, Tang B, He J. Shot Peening and Solid Lubricating on Ti6al4v Fretting Fatigue. Rare Metals. 1999 ;18(3):229-234.
122 . Crump S, Burguete R, Sim W-, De Oliveira A, Van Der Veen S, Boselli J, et al. A Concurrent Approach to Manufacturing Induced Part Distortion in Aerospace Components. Materials Science and Technology. 2005 ;475-86.