

An energetic approach to predict the effect of shot peening based surface treatments

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Abstract: Almen intensity and surface coverage are well-known to be the defining parameters of shot peening based surface treatments. These parameters are directly affected by material properties, the extension of the contact zone, the geometry of the impact pair as well as impact rate and velocity. These intricate relations have resulted in often dissimilar predictions of shot peening effects even while using identical combination of Almen intensity and surface coverage. With the introduction of new generation of impact based surface treatments, there is a need to find a more widespread parameter that would facilitate direct comparison of all different treatments and relate the main process parameters with the resultant mechanical characteristics.

Herein, we propose to use an energy based parameter to describe the peening process as a more universal approach, which incorporates collectively the effects of Almen intensity, surface coverage as well as diameter, material, and velocity of the impact media. A set of finite element analysis was developed to demonstrate the correlation of peening process effects with this energetic approach. Comparison with experimental data also confirmed that the proposed method could provide a quite good estimation of the effect of peening parameters on the treated material.

Keywords: shot peening; impact-based surface treatments; kinetic energy; Almen intensity; surface coverage

1. Introduction

Shot peening is a surface treatment mainly known for its favorable effects in enhancing fatigue strength of mechanical components. It has been widely used in machinery, aerospace, automotive industry and railway systems for decades. This process consists of impacting material surface with high velocity peening media (mainly steel shots or ceramic beads), to generate inhomogeneous plastic deformation and consequently induce compressive residual stresses on the surface layer of the treated material. With the advancement of technology and development of high tech equipment, the concept of shot peening, which is based on inducing plastic deformation with repetitive high frequency impacts, has been recently extended to a vast range of cutting-edge impact-based surface treatments. The new generation of surface treatments are developed to amplify the desirable effects of the conventional shot peening for a wider variety of applications ranging from classic industrial applications to biomedical ones [1-5]. These processes can be listed as ultrasonic shot peening (USSP) [6, 7], high energy shot peening (HESP)[8], surface mechanical attrition treatment (SMAT) [9-12], surface nanocrystallization and hardening [13], severe shot peening (SSP) [4, 14, 15], sandblasting and annealing [16], ultrasonic impact treatment (UIT) [17] and ultrasonic impact peening [18], to name just the most noted ones. It is also to be underlined that some of these methods are basically using the same setup and mechanism and have been named differently due to the lack of consistency in the literature. Nevertheless, what all these methods have in common is the application of severe plastic deformation through high energy impacts to induce grain refinement, hardening, and compressive residual stresses through recurrent impacts of either shots, balls or pins using various loading schemes. Whatever the apparatus and loading arrangement, the obtained results are mainly influenced by a few parameters that all the aforementioned peening treatments share. The critical parameters are the indentation size produced by a single impact, which is in turn affected by impact velocity and impacting

media's material and geometry, as well as the total exposure time; exposure time is the duration of the peening treatment when the target material is being impacted by the peening media. These factors are practically set through two pragmatic parameters used in conventional shot peening to control the consistency and facilitate replicating of the process, i.e., Almen intensity and surface coverage. Almen intensity is the industrial measure of the kinematic energy of the shot stream and is calculated by measuring the curvature of standard Almen strips exposed to shot stream at saturation point. Saturation point refers to the first point on the arc height vs. exposure time curve, where doubling the exposure time does not change the arc height more than 10% [19]. Although recognized as the universal parameter of shot peening, estimation of Almen intensity is not straightforward and necessitates the use of apposite Almen strip and Almen gauge. Surface coverage, on the other hand, is the ratio of the plastically deformed area to the whole treated surface area. Considering the exponential behavior of surface coverage over time, coverages higher than 98% (highest surface coverage that can be measured visually also known as full coverage) are estimated by multiplying factors to the time required to reach full coverage [20].

For a long time, many researchers have tried to provide empirical graphs, formulations and numerical simulations to relate these main process parameters with mechanical behavior of the treated material. There are few successful efforts regarding distribution of residual stresses [21-23], work-hardening [24] and the induced surface roughness [25]. However, most available approaches are either limited to specific sets of process parameters and limited materials or are applicable to a range of process parameters and thus cannot be straightforwardly generalized. Besides, Almen intensity and surface coverage themselves are associated with multiple process parameters. For example, surface coverage is directly affected by the interaction between the impact pair, their material properties, and the contact zone, which are in line affected by shot and target material geometry as well as mass flow and peening velocity. Hence, there are reports of obtaining different distributions of residual stresses and extensions of plastically deformed areas, using the same combination of Almen intensity and surface coverage [26, 27].

Herein, we propose that rather than using a combination of parameters like Almen intensity, shot diameter, shot material, shot velocity and surface coverage to provide an inclusive estimation of the effect of peening parameters on the functionality of the treated material, a single parameter that is directly related to the impact energy can be used for this purpose. A finite element model (FEM), previously developed by the authors [14] and updated incorporating varying impact angles and implementing both single impact and multiple impacts, has been used to prove the concept of the idea. The suggested energetic approach entails the effect of all factors associated with the media stream including its size, material properties and velocity into one single parameter and has the potential to be generalized for any impact based surface treatment. A set of experimental test data, for which we had access to all the process parameters and residual stress distribution, were simulated by FEM analysis to check the prediction of the energetic approach and assess its validity.

2. Description of the finite element model

The kinetic energy of the shots upon impact is here considered as the key parameter dictating the ensuing effect of the process on the treated material. Based on the properties of the contact pair, fractions of energy are consumed to result in plastic deformation, friction and surface damage production in the form of a potential fracture and possible heat production. Assuming that the friction induced heat and fracture can be negligible, the main portion of the transferred energy is absorbed for plastic deformation and indentation formation on the target surface. Here, we have developed a numerical model based on a FEM analysis of SSP process previously presented by the authors [14]. The model is developed using commercial software Abaqus/Explicit 6.12 and consists in a rectangular block of (3×3×1.5 mm³) with a central impact area of (1×1×0.5 mm³) both meshed using C3D8R elements. The bottom part of the model was covered by infinite elements to provide stable results after impact. Chaboche nonlinear isotropic/kinematic (combined) hardening model for AISI 304L stainless steel was used as the constitutive model of the target material [28]. Steel shot, on the other hand, was modeled as an elastic semi-sphere (doubling the density to reduce the number of elements while maintaining the kinetic energy) meshed using C3D4 tetrahedral elements. Mesh convergence study was performed following the approach adopted in [29] considering both distributions of residual stresses and equivalent plastic strain (PEEQ) in the impact zone. Accordingly, element size of 1/20th and 1/10th of the average single indentation diameter were used to mesh the impact zone and the shot

respectively. Shot velocity was considered as a vector indicating the impact angle and its absolute velocity. The interaction between the shot and the impact area was defined as a general contact with a coulomb friction coefficient of $\mu = 0.2$. The reader is directed to the original paper [14], for additional details on the FEM analysis.

3. Single impact model

Plastic indentation size is of primary importance in characterizing the impact-based surface treatments since it actually connects and controls the main two parameters of Almen intensity and surface coverage. Increased indent size corresponds to the higher Almen intensity and results in higher surface coverage, for a given number of impacts [30]; it will consequently affect induction of residual stresses, surface work hardening, surface roughness and topographical morphology.

It is known that as the shot impacts the surface and rebounds, a portion of its initial kinetic energy ($\frac{1}{2}mv^2$) will cause deformation in the target material. Since the indent size is directly modulated by the converted kinetic energy, this energy can be considered as a decisive parameter, which affects all the subsequent outcomes of the peening treatment. Considering the importance of plastic indentation size, this initial single impact analysis is devoted to provide an accurate estimation of it. There are few simple empirical equations suggested for estimation of the indentation size. Kirk [30, 31] took the effects of shot diameter (d), its density (ρ) and velocity (v) as well as target material properties into account to evaluate the indentation size. In this approach, target surface Brinell hardness ($[kgf/mm^2]$) and the coefficient of restitution (e) were considered to assess the interaction of the shot and the target surface. This coefficient is to account for the retained energy as the shot bounces off the target surface and is defined as in Eq. 1 in which h_1 is the initial drop height of the shot and h_2 is the height it bounces off upon impact on the flat surface. Kirk [30] suggested that e can be reasonably estimated to be 0.71 for the interaction of steel shot with steel surface. Eq. 2 and Eq. 3 are proposed by Kirk to correspondingly predict the circular indent diameter (d) and depth (h) for vertical impacts assuming the shots are all spherical [30, 31]. D is the shot diameter, ρ (kgm^{-3}) is shot density, v (ms^{-1}) is shot velocity and B stands for Brinell hardness.

$$e = \sqrt{h_2/h_1} \quad (1)$$

$$d = 0.2284 D(1 - e^2)^{0.25} \rho^{0.25} v^{0.25} / B^{0.25} \quad (2)$$

$$h = \frac{[D - (D^2 - d^2)^{0.5}]}{2} \quad (3)$$

Iida [32] also proposed the following empirical equations for indent diameter and depth estimation, where v is the shot velocity, D is shot diameter and k_d and k_h are experimentally obtained constants related to the Vickers hardness of the treated material.

$$d = k_d D v^{1/2} \quad (4)$$

$$h = k_h D v \quad (5)$$

Fig.1 (a) and (b) represent the good agreement between the indent size obtained from single impact FEM model and the Kirk and Iida empirical estimations in terms of indent diameter and depth, varying the impact velocity for a constant shot diameter of 0.6 mm, considering density of 7800 kg/m^3 and Brinell hardness of 201 HB. The results confirm the clear effect of impact velocity on increasing the indent global size. Kirk and Iida formula provide almost identical estimations for indent diameter but diverge slightly for estimation of indent depth at higher velocities.

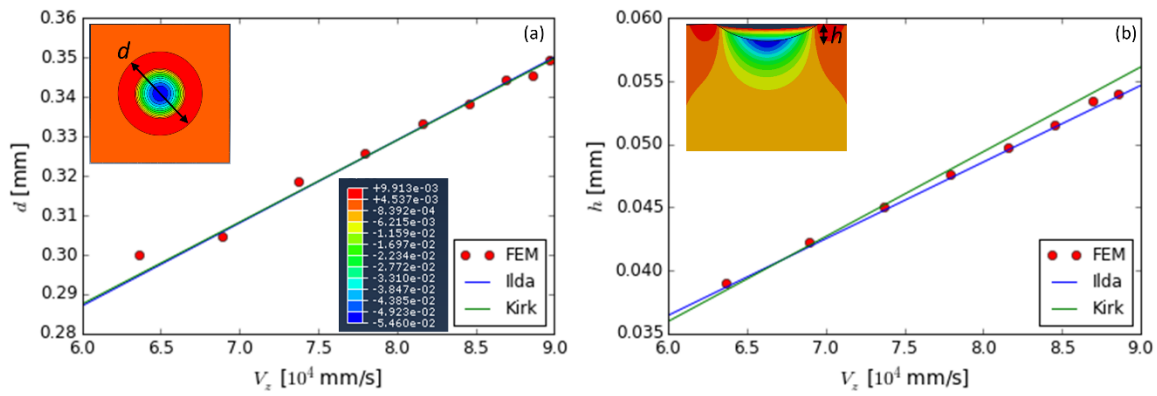


Figure 1. Comparison of the indent size diameter and depth estimated by Kirk and Iida empirical equations with the data obtained from single impact FEM analysis (vertical impact, shot diameter: 0.6 mm, shot density: 7800 kgm^{-3} , Brinell hardness: 201 HB); the inserts are representative vertical displacement contours; the stress range is corresponding to both inserts.

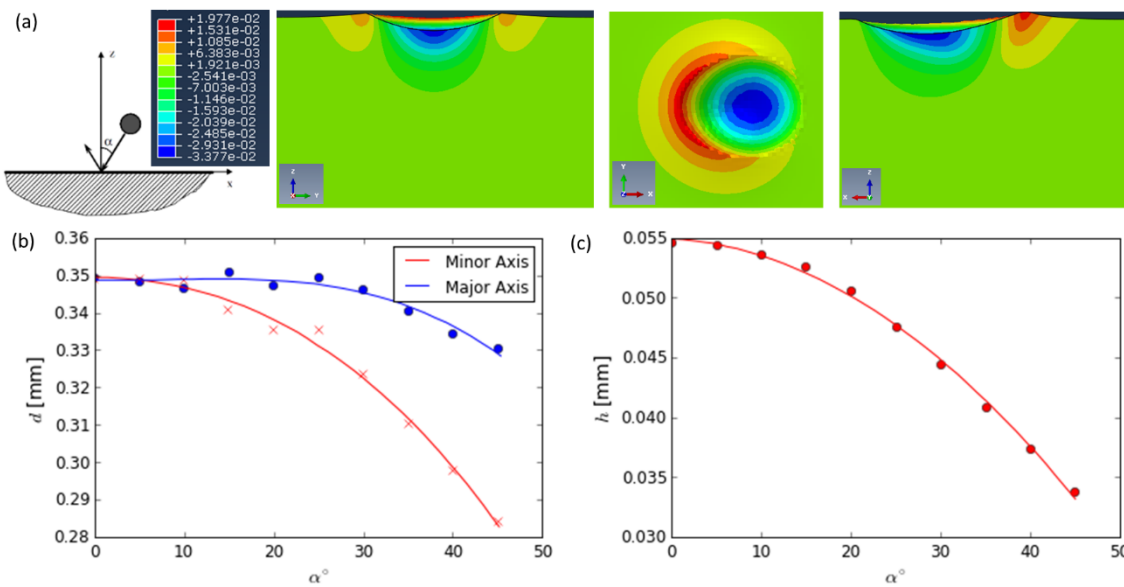


Figure 2. (a) Different views of elliptical indent generated by an oblique impact represented in vertical displacement contours. Prediction of ellipse indent size for oblique impacts (shot diameter=0.6 mm, shot velocity= 60 mms^{-1}) obtained from single impact FEM analysis (b) major and minor axis (c) ellipse max depth.

Contrary to the assumptions of these empirical equations, in practice, shots are not ideally striking the component surface perpendicularly, due to the divergence and interaction of the shot stream as well as possible curvature and geometrical discontinuities in the work piece. This impact angle affects the Almen intensity and the surface coverage; therefore, a more realistic estimation of the effects of peening process can be obtained by taking the effect of impact angle into account. The experimental data provided by Kirk [30] and the FEM results here confirm that by changing the impact angle from 0° , the dent circular shape changes to an ellipse with a varying depth and pile up size compared to the constant size and symmetric assumption considered for the precedent empirical equations.

The variation of the ellipse major and minor axes for oblique impacts can be observed in Fig. 2 as a function of impact angle for a shot diameter of 0.6 mm and impact velocity of 60 mm/s. Hong et al. [33], confirm that highest residual stresses are obtained at angles closer to vertical incident direction. In this study, angles higher than 45° were not taken into consideration, as they considerably reduce the desirable effects of the surface treatment and in practice are normally avoided. These results indicate that the ellipse diameter in the x-direction, that is the direction of the horizontal component of impact velocity, decreases more slowly compared to the diameter in the perpendicular axis. It is also observed that by increasing the impact angle, that is reducing the vertical component of velocity vector, the indent size and the amount of energy converted to

plastic deformation decreases, reducing the subsequent residual stresses and work hardening effects. Fig. 3 represents the relation between the initial kinetic energy of the shot and the indent diameter considering steel shot and perpendicular component of oblique impacts velocity. Higher shot diameter naturally increases the indent size, but in case of oblique impact, the variations of major and minor ellipse axis have different trends caused by the reduction of the vertical component of kinetic energy and the presence of a horizontal energy component.

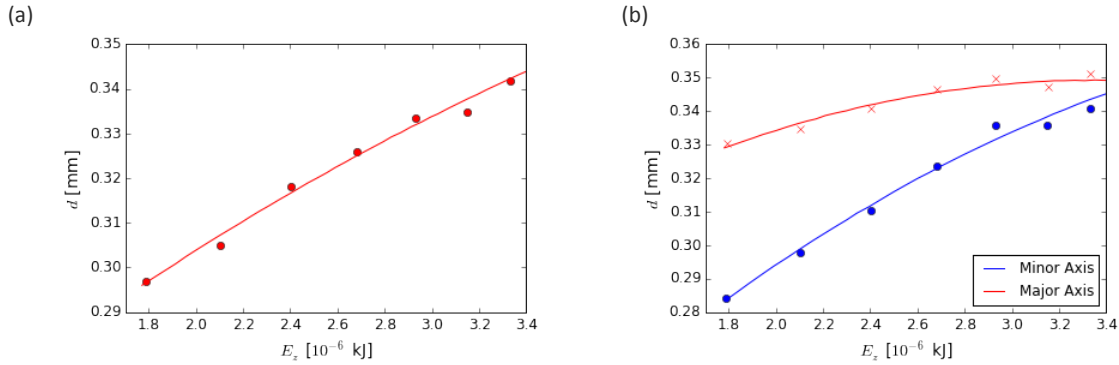


Figure 3. Variation of the dimple diameter as a function of the vertical component of the shot kinetic energy (a) perpendicular impact (b) oblique impact (shot diameter=0.6 mm, shot velocity=60 mms⁻¹).

4. Multiple impact model

We performed multiple impact analyses with a slightly reduced model size compared to single impact (0.25×0.25×0.5 mm³) to moderate the computational costs without affecting the obtained distribution of residual stresses. This model is aimed at evaluating the effects of multiple inclined impacts with regard to the residual stress and PEEQ. In particular, we investigated the effects of the most significant parameters such as impact angle, shot diameter, shot velocity and the required surface coverage.

Random surface coverage in term of impact position and sequence was adopted following the subroutine previously developed by the authors [20] for a realistic simulation of surface coverage during multiple impact peening process. The subroutine that is based on the exponential Avrami approach for full coverage estimation [34], was updated incorporating the possibility of imposing random impact angle for each individual shot and estimating the corresponding indent elliptical area. Fig. 4 represents the top and front view of the positioned multiple shots obtained from implementation of the coverage subroutine.

Having defined all the details of the model, a Design of Experiment (DOE) method was adopted to determine possible dependencies between the main peening parameters including shot diameter (d=0.42, 0.06, 0.85 mm), shot velocity (v=40, 50, 60, 70 m/s), impact angle ($\alpha=0, 15, 30, 45$) and surface coverage (C=100, 300, 500%). Considering elastic shots and neglecting the dissipation of thermal energy during shot peening, the energy that is absorbed for plastic deformation of the target material can be extracted from the difference between the shot kinetic energy just before and after the impact. The deformation energy for a single vertical impact can be estimated by Eq. 6, in which E is the kinetic energy, V_i is the initial velocity of the impact and V_r is the rebound energy.

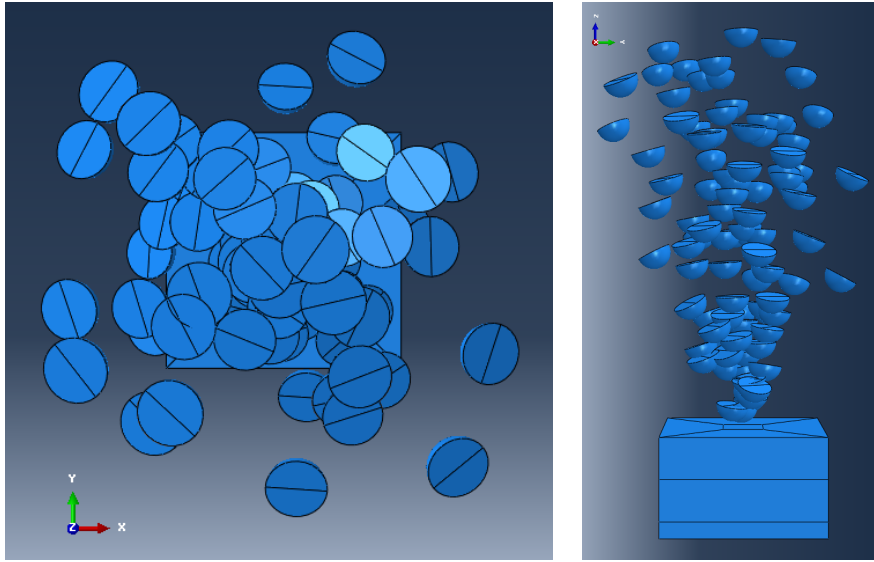


Figure 4. Top and side view of the randomly positioned multiple impact model

In the case of oblique impact, the variation of kinetic energy is influenced by both vertical and horizontal components of the velocity considering that the friction phenomena (characterized by Coulomb friction [35]), introduces a significant contribution. In particular, by increasing the incident angle, the horizontal component of velocity becomes comparable with the vertical one. This considers the dissipated energy caused by local sliding of the shot on the target surface. Therefore, the energy introduced into the process, in order to deform the surface of the component, is defined considering both components of shot velocity before and after impact and the total energy considered in the analysis is the sum of energy variation of all the impacting shots (Eq. 7).

$$\Delta E_{Kin(\alpha=0)} = \frac{1}{2} m (V_i^2 - V_r^2) \quad (6)$$

$$\square E_{Kin}^{tot} = \sum_{i=1}^N \square E_{Kin}^i \quad (7)$$

Fig. 5 shows the trend of the average PEEQ on the surface layer of the target material for multiple impact model as a function of transmitted kinetic energy per unit area (The transmitted kinetic energy is normalized by the total impact area). One analysis performed with shot diameter of 0.85 mm, vertical velocity of 70 ms⁻¹ and a surface coverage of 800%, much higher compared to the range used in the DOE analysis, is added to consider the case of SSP that is aimed at surface nanocrystallization. The results indicate clear initial increase of PEEQ as the transmitted kinetic energy is increased. For much higher impact kinetic energies, however, the PEEQ values tend to grow much more gradually, as it can be observed for the SSP case. From the analysis presented here, it is, therefore, possible to determine the formula (Eq. 8) which allows obtaining the value of the PEEQ as a function of the energy of unit area, with an acceptable fit.

$$PEEQ(E) = \frac{-169.1E^2 + 6.799E - 0.0001602}{E^4 + 41.56E^3 - 36.51E^2 + 0.43E + 0.0002346} \quad (8)$$

In order to validate this energetic approach, we needed to compare its results with some experimental data on materials for which we have access to all the experimental details in terms of process parameters and measured residual stresses in order to be able to calculate the kinetic energy of the impacts. The experimental data presented here are obtained from our previous experiments performed on two low alloy steels 39NiCrMo3 (UNI EN 10083) [11] and 40NiCrMo7 (UNI 7845) [36]. Table 1 reports the general mechanical properties of these two steels. Numerical models were developed using a range of process parameters covering the ones used in the aforementioned experiments and incorporating the Chaboche

material properties of the corresponding steel. Fig. 5 (b) show represents the comparison of the available experimental data and the numerical ones, where a good correspondence can be observed.

Table 1. General mechanical properties of 39NiCrMo3 and 40NiCrMo7 steel.

Steel	Elastic modulus (GPa)	Yield modulus (MPa)	Ultimate tensile stress (MPa)	Elongation (%)
39NiCrMo3	210	734	908	14.8
40NiCrMo7	203	1170	1290	14.9

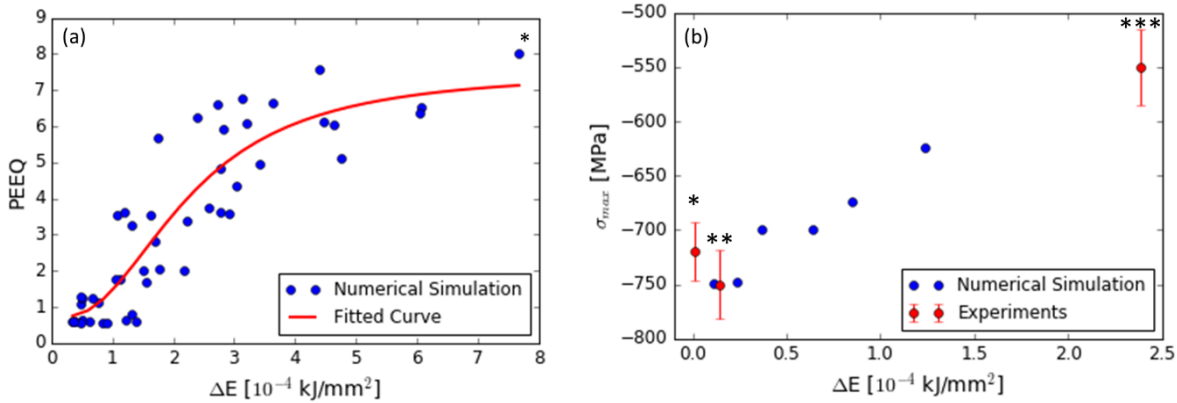


Figure 5. (a) Surface PEEQ variation in the multiple impact model as a function of the kinetic energy per unit area (the topmost data point on left is representing severe shot peening cases) (b) Max in-depth residual stress obtained by FEM compared with compared to experimental data (*corresponds to experimental data for 40NiCrMo7 (shot size 0.3 mm, Almen intensity 4-6A (0.0001 in.) and 100% coverage) ** corresponds to experimental data for 40NiCrMo7 (shot size 0.43 mm, Almen intensity 10-12A (0.0001 in.) and 100% coverage); *** corresponds to experimental data for 39NiCrMo3 (shot size 0.6 mm, Almen intensity 7C (0.0001 in.) and 1500% coverage)).

5. Conclusions

An energetic approach was suggested to substitute the combined use of various process parameters in impact based surface treatments including Almen intensity, surface coverage as well as size and material properties of shots. This approach is based on the portion of the normalized kinetic energy used up for plastic deformation of the target surface.

The obtained finite element results indicate that equivalent plastic strain is highly correlated with the normalized kinetic energy of the impacts. This energy parameter can be adopted to estimate the effect of impact-based surface treatments on the treated material in terms of equivalent plastic deformation and residual stresses. As a proof of concept the validity of this method was evaluated using experimental data for which all the necessary input parameters for the simulation were available. Comparison with experimental data point out that kinetic energy has a high potential to substitute other process parameters and provide a good estimation of residual stress state. This method can be considered the first step toward developing a purely energetic approach; more controlled experiments covering a wide range of parameters would be needed to thoroughly verify the applicability of this approach.

Conflicts of Interest: The authors declare no conflict of interest

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