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A novel approach for modelling of water jet peening

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Abstract

In this paper, a novel approach, proposed for predicting residual stresses induced on materials treated with high pressure water jets, i.e. water jet peening, is presented. This approach considers the impact pressure distribution due to high velocity droplets impinging on the material surface instead of stationary pressure distribution considered in Trans ASME J Eng Mat Technol 121 (1999) 336 for prediction of residual stresses on water jet peened surfaces. It makes use of Reichardt's theory for predicting the velocity distribution of droplets and liquid impact theory for predicting the impact pressure and duration of impact of high velocity droplets. For predicting residual stresses on the surface and sub surface of material subjected to water jet peening, finite element modelling approach was adopted by considering the transient, dynamic nature of droplets for analysis. The effectiveness of the proposed approach was demonstrated by comparing the predicted residual stresses with those predicted employing the approach proposed in Trans ASME J Eng Mat Technol 121 (1999) 336. Finally, the practical relevance of the proposed approach was shown by comparing the predicted results with the experimental results obtained by water peening of 6063-T6 aluminium alloy.

Keywords: Water jet peening; Surface treatment; Residual stresses; Numerical modelling; Transient dynamic analysis

1. Introduction

Water jet peening is a cold working process that can impart compressive residual stresses in the surface and subsurface layers for enhancing the fatigue life of components used in aerospace and automobile industries. In this process, high velocity water droplets continuously impinge over the surface. These droplets produce high peak loads that can cause localized plastic deformation of material and stretching of the layers of the surface. Upon unloading, the elastically stressed sub surface layers tend to recover to original state, but the continuity of material in both elastic and plastic zones does not permit this to happen. Consequently, a compressive residual stress followed by tensile stress is trapped in the treated component. Therefore, it is a force-controlled treatment that generates compressive residual stresses in the surface layers without modifying the surface topography. Unlike shot peening, this process is relatively easy to control due to less number of variables such as water jet pressure, nozzle geometry, stand off distance and peening duration influencing the process. Further, this process is capable of treating the entire surface uniformly thus requiring simplified quality assurance procedures.

Attempts made to investigate the capabilities of water jet peening for treating different materials are mostly experimental in nature. These studies clearly indicated the need to choose process parameters such as water jet pressure, stand off distance and jet diameter carefully for treating different materials with water jets [1–4]. On the other hand, most of the attempts made to model the process are empirical in nature. Recently, Daniewicz and Cummings [5] made an attempt to analyze the water peening process with finite element methods. In this work, it was assumed that a high velocity water jet, impinging on the surface, exerts pressure equivalent to stagnation pressure. The analysis was made by considering this pressure on an elastic plastic space with kinematic strain hardening. For

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Nomenclature

A	cross-sectional area of water jet (m^2)
C_1	shock velocity of water (m/s)
C_0	Acoustic velocity of water (m/s)
E	Young's modulus (GPa)
E_t	Tangent modulus (GPa)
F	total force (N) of water jet
K	constant for water in the velocity range up to 1000 ms^{-1}
P_{imp}	impact pressure (GPa)
p	intensifier pressure (MPa)
p_o	stagnation pressure (MPa)
p_s	stationary pressure (MPa)
r	arbitrary radial distance from the center of impinging jet (mm)
r^*	outer radius of the circular region exposed by the jet (mm)
r_n	radius of the nozzle (mm)
r_w	radius of the water droplet (μm)
r_c	contact radius of droplet (μm)
r_{eff}	effective contact radius of droplet (μm)
t_l	loading time (seconds)
t_u	unloading time (seconds)
u_{max}	maximum exit velocity of water jet (m/s)
u	average exit velocity of water jet (m/s)
σ_y	yield stress (MPa)
ρ	density of water (kg/m^3)
v	Poisson's ratio

better results, it was suggested to adopt a more rigorous simulation considering a moving pressure distribution along the surface and shake down effects when moving jet is passed over the same region several times to cover the entire surface. It is well reported that high velocity droplets in droplet region are responsible for inducing compressive residual stresses on the surface and sub surface layers treated with water jets [5]. Hence, the present work attempts to consider the impact of liquid droplets on a solid surface for analyzing water peening process. As several water droplets impinging on a surface result in the generation of compressive residual stresses on the treated surface, it is felt appropriate to consider the simultaneous impact of several droplets in predicting the stresses generated over the surface.

Heymann [6] reviewed the dynamics of high-speed impact between a compressible liquid drop and a solid surface. The collision of a liquid drop with a rigid surface was analyzed rigorously as shown in Fig. 1(a) [7]. When a high velocity liquid drop is impinged over a rigid plane surface, the shock front created during initial period of impact remains attached at the instantaneous contact perimeter without any tangential outflow. During this period, the instantaneous contact pressure becomes maximum at the contact perimeter of the drop. The critical edge pressure corresponding to the contact angle between the drop surface and the target material is assumed to reach three times the water hammer pressure as shown in Fig. 1b. However, it is valid to consider water hammer pressure in the central region of the droplet.

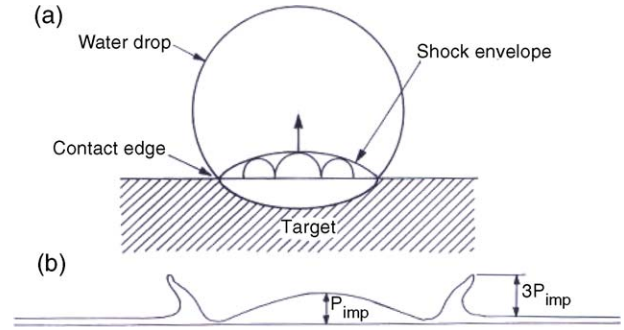

Fig. 1. (a) Initial stage of a liquid drop impact on a solid surface [7]. (b) The shape of a liquid drop and the distribution of pressure in different regions after a certain time of impact.

Attempts were made to analyze the shot peening process by considering the variation in size, the velocity of shots and the separation distance between co-indenting shots. Meguid et al. made a three-dimensional dynamic finite element analysis of shot peening and showed that the depth of compressed layer, surface and sub-surface residual stresses are significantly influenced by shot velocity, shot shape and the separation distance between co-indenting shots. Impact of multiple shots on the surface results in a more uniform residual stress field on it [8,9].

From the above, it is appropriate to think of considering the impact of several water droplets on the surface in order to predict the stresses generated on the surface. As each droplet exerts an impact pressure over a very short duration, the present work attempts to consider an impact of high velocity droplets and carry-out transient dynamic analysis for predicting the residual stresses generated on water peened surface.

2. Methodology

Fig. 2 shows the structure of jet propagating in air. Among the different zones, the droplet zone is responsible for generating compressive residual stresses on the surface treated with water jets [2,3]. Since the water droplets impinging on the solid surface are likely to have different velocities, the impact pressure and duration of these droplets will be different [7]. Hence, it is essential to consider this variation in droplet impact pressure and duration of impact for modeling and analyzing this process.

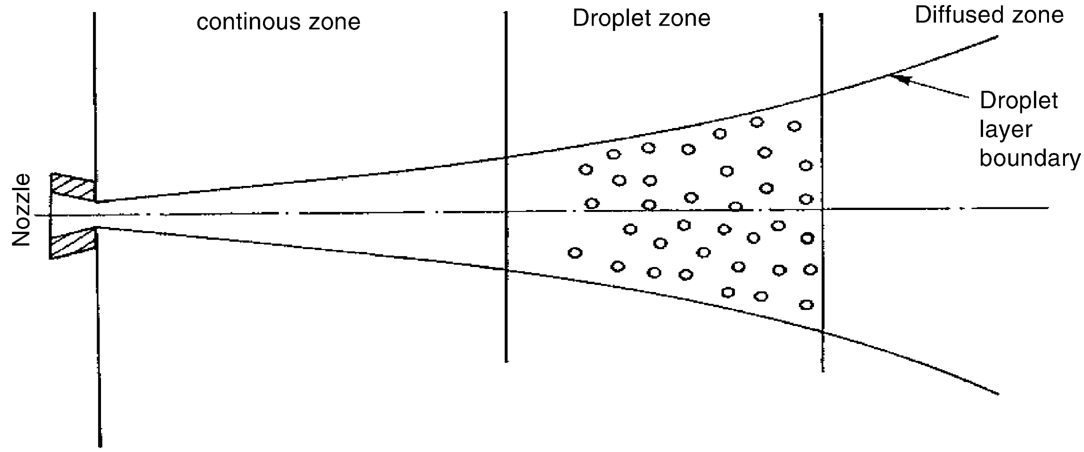

Fig. 2. Structure of water jet in air [10].

Different steps adopted for predicting residual stresses on the surface are:

1. To determine the intensity of impact pressures from the velocity distribution of water droplets by employing Reichardt's theory [10] and the duration of impact of droplets by using liquid impact theory [7].
2. To predict the residual stresses induced on the surface with high velocity water droplets by means of transient dynamic elastic plastic finite element analysis.
3. To compare the residual stress profiles predicted with the proposed model with those obtained by stationary pressure distribution acting on the surface for the purpose of demonstrating the effectiveness of the proposed model.
4. Finally, to assess the practical relevance of the proposed model for predicting residual stresses on water peened surface by comparing the predicted results with experimental results.

2.1. Distribution of impact pressures generated by water jet

By assuming the size of droplets of water as small and their distribution as uniform in the droplet region, the velocity of water droplets in the region is determined by using Reichardt's theory and is given as [10]

$$\frac{u}{u_{\max}} = \left[1 - \{r/r^*\}^{3/2}\right]^2 \quad (1)$$

$$u_{\max} = \sqrt{2P/\rho} \quad (2)$$

where $u_{\max}$ is the exit velocity of water jet from the nozzle, r is the arbitrary distance from the axis of jet, r^* is the maximum radial distance of exposed jet, P is the pressure of water entering the nozzle and ρ is the density of water.

To determine the maximum radial distance of exposed jet at different locations from the nozzle end, a momentum balance of jet in different locations was applied. When the jet strikes the surface, it exerts force (F) normal to the specimen and is given as [5]

$$F = \rho A \ u_{\max}^2 \quad (3)$$

where A is the cross-sectional area of jet and $u_{\max}$ is the exit velocity of water jet.

The total force (F) exerted by water jet can be written as

$$F = \int_A P \mathrm{d}A \quad (4)$$

$$F = \int_0^{r^*} \rho u^2 \ 2\pi r \ \mathrm{d}r \quad (5)$$

$$\int_0^{r^*} \rho \ u^2 \mathrm{d}A = \rho u_{\max}^2 2\pi \int_0^{r^*} \left[1 + \left(\frac{r}{r^*}\right)^3 - 2\left(\frac{r}{r^*}\right)^{1.5}\right]^2 r\mathrm{d}r \quad (6)$$

By integrating Eq. (6) and equating it with momentum balance, the radial distribution of water jet is obtained as

$$\frac{r^*}{r_n} = \sqrt{7.518} \frac{u^2}{u_{\max}^2} \quad (7)$$

In droplet region, the droplets of jet can be considered to be turbulent. For turbulent flow of water jet,

$$\frac{u}{u_{\max}} = 1.$$

Therefore,

$$\frac{r^*}{r_n} = 2.74 \quad (8)$$

where r_n is the radius of the nozzle.

By substituting Eq. (8) into the Eq. (1), the velocity distribution of water droplets is obtained as

$$\frac{u}{u_{\max}} = 1 + 0.0484\left(\frac{r}{r_n}\right)^3 - 0.44\left(\frac{r}{r_n}\right)^{1.5} \quad (9)$$

In order to predict the impact pressure distribution on the surface by the droplets of jet, the present work made use of the theory of liquid impact. The same theory was used to obtain the impact duration of droplets within the droplet region.

According to liquid impact theory, the high-speed compressible liquid drop striking a solid surface generates 'water hammer pressure'. When the drop is flattened, it exerts high pressures in the periphery of contact region, in contrast to water hammer pressure in the central region of liquid drop [7]. Hence, this work attempted to consider an uniform impact pressure of water droplets, i.e. water hammer pressure over the effective contact radius. Several assumptions are made in modeling the process for predicting residual stresses induced on the work surface and are as follows.

(a) Water droplets are spherical in shape and are uniformly distributed over the striking region.
(b) Friction between the droplets of water and the surrounding air is ignored.
(c) Flow of jet is uniform at the exit of nozzle and no external forces act on the jet.
(d) The distribution of droplets is uniform with a constant exit velocity in the central region of droplet zone.

The impact pressure (P_{imp}) exerted by water droplet on the surface is directly proportional to the droplet exit velocity and shock velocity of water and is given by [7]

$$P_{imp} = \rho \ u_{\max} \ C_1 \quad (10)$$

where $u_{\max}$ is the exit velocity of water jet and C_1 is the shock velocity of water.

The shock velocity of water (C_1) can be determined from the relation [7]

$$C_1 = C_0 + k \ u_{\max} \quad (11)$$

where C_0 is the acoustic velocity of water jet and k is a constant, which is close to 2 for water in the velocity range upto 1000 ms^{-1} [7].

The contact radius of droplet (r_c) is determined with the relation [7]

$$r_c = r_w \ u_{\max}/C_1 \quad (12)$$

where r_w is the radius of water droplet in the region of impact.

The high-pressure stage terminates after a certain time of impact of each droplet. The impact duration of droplets in the droplet region of jet during loading 't_l'and unloading 't_u' can be estimated from the relations [8]

$$t_l = 3 \ r_w \ u_{\max}/2C_1^2 \quad (13)$$

$$t_u = 3 \ r_w \ u_{\max}/2C_1^2 \quad (14)$$

By knowing the location of droplet from the axis of jet along the radial distance, the average velocity of water droplet in that region can be determined. For water droplets having different velocities, the impact pressure and duration of impact of water droplets can be determined. These data are used in the finite element modeling of water peening process.

2.2. Residual stresses on water peened surface

Fig. 3 shows a schematic diagram illustrating the methodology adopted in modeling of water peening process. The proposed model considers water jet pressure and nozzle bore diameter in order to determine the velocity distribution of droplets in the droplet region, impact pressure and impact duration of droplets striking different locations on the surface.

During the initial period of water jet peening, randomly oriented droplets having different velocities, strike the surface at different intervals of time. In view of a very short duration of these droplets impacting the surface, successive droplets in this region continue to strike the surface in the duration of peening. In a very short duration of impact of droplets, the material undergoes plastic deformation. Upon unloading, certain residual stresses are left on the surface and subsurface layers.

The proposed model considers a set of droplets, located adjacent to each other in a single row, strike the surface thus exerting an impact pressure over a finite region of contact at different locations of the surface. Such an impact of droplets is assumed to generate compressive residual stresses on the surface. Fig. 4 shows the random distribution of droplets in the droplet region, which are assumed to be striking the surface in an orderly manner. Since these droplets distributed uniformly exert uniform impact pressure over a finite region of contact, it is proposed to consider the contact radius of approximately 0.0625 mm for a droplet size

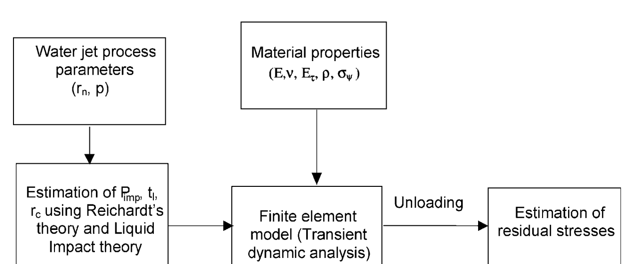

Fig. 3. A schematic diagram illustrating the modelling of water peening process.

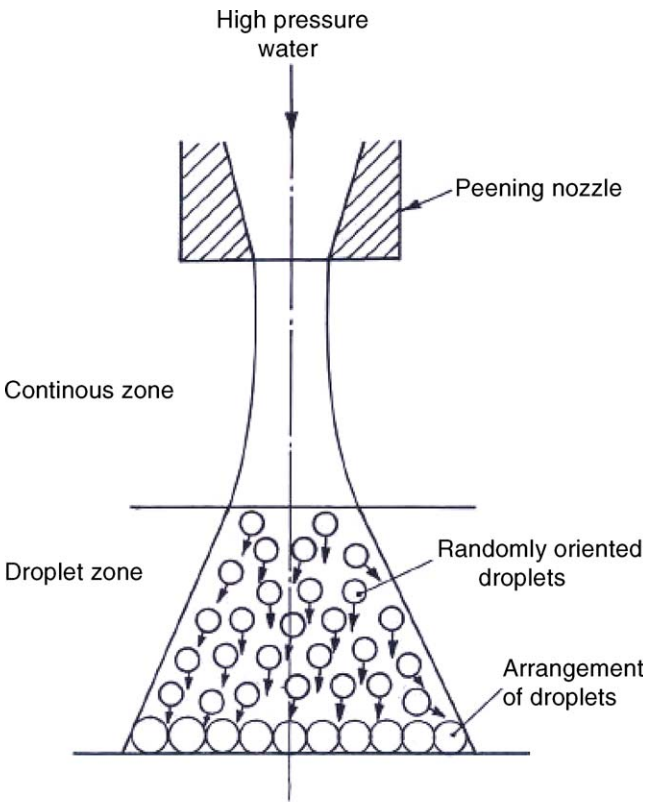

Fig. 4. A schematic diagram showing an impact of single set of droplets on the material surface.

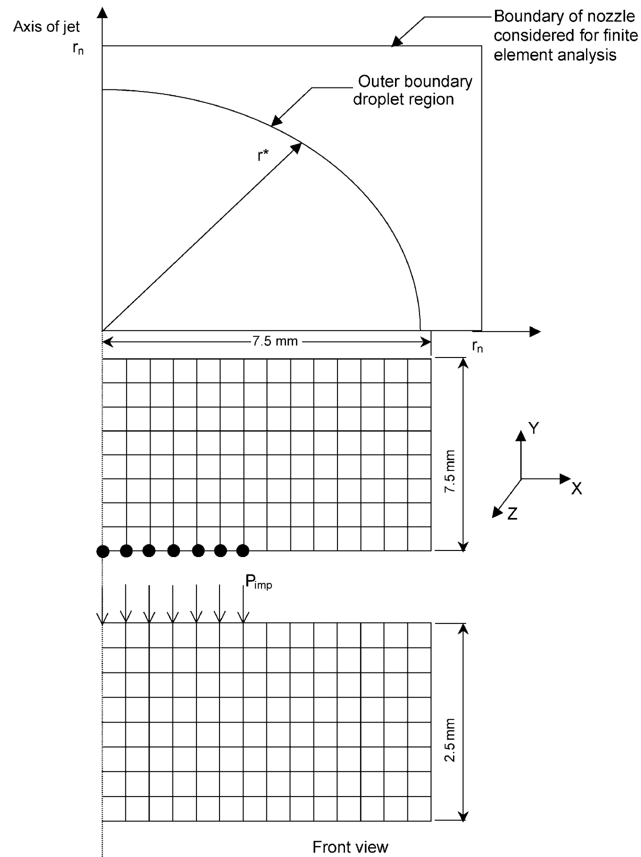

Fig. 5. Finite element model of region subjected to droplet impact pressure.

of 0.250 mm radius. This has resulted in the selection of a mesh size of 0.125×0.125 mm for modelling the process.

In practice, each region will have an impact of several droplets over the duration of peening. For the sake of simplicity, the present model considers an impact of one set of droplets over the region. Eddingfield and Evers [11] suggested that a droplet with a diameter greater than 500 μm will be subjected to secondary break up. Thus, the size of droplet is assumed to be less than 500 μm. With this assumption, a mesh size of 0.125×0.125 mm was considered over the region of $7.5 \times 7.5 \times 2.5$ mm as shown in Fig. 5. This particular mesh size corresponds to an effective contact radius of droplets, i.e. 0.0625 mm. For a droplet size of 0.250 mm, the Weber number (We) is 52 with a relative velocity equal to 50% of a jet velocity [11]. The analysis was carried out using transient dynamic finite element analysis feature available in ANSYS 6.0 [13].

To determine the residual stresses generated on the surface treated with water jets, the dynamic pressure estimated from the droplet impact velocity, corresponding to intensifier pressure and nozzle bore diameter, was assumed to act over the region for a very short duration. In transient dynamic finite element analysis, the response of material is considered to be bilinear plasticity and is represented by two slopes. In view of small strains exerted by the droplets for a very short duration, the material is assumed to undergo kinematic strain hardening for isotropic materials. For the purpose of analysis, an impact of droplets of water on one quadrant of surface was considered for simulation by applying axi-symmetric impact pressure distribution at different nodes in the region. Four noded quadrilateral finite element having two degrees of freedom PLANE 42 was used to discretize the target into a fine grid of 0.125×0.125 mm.

Fig. 6 shows the exact location of droplets exerting impact pressure (P_{imp}) on a surface considered for modeling. The expression $r_i = (2i-1)\, r_w/2$, where $i = 1, 2, 3, \ldots n$. Let the axis of water jet be the reference axis for identifying the location of any droplet on the surface at the exit end of a round nozzle, having a radius r_n, with uniform velocity distribution. r_{eff} is the effective contact radius of the droplet and r^* is the outer radius of jet exposed. A uniform pressure of (P_{imp}) is applied over an area of 7.5×7.5 mm, for a duration of 't_1', i.e. loading time that follows ramp loading as shown in Fig. 7. With the application of uniform pressure (P_{imp}) over the region following ramp loading pattern for a duration of

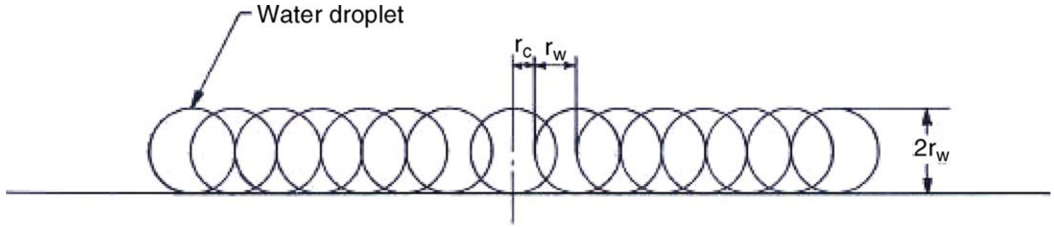

Fig. 6. A schematic location of droplets showing the exerting impact pressure of $P_{imp} = (2i-1)\ r_w/2$.

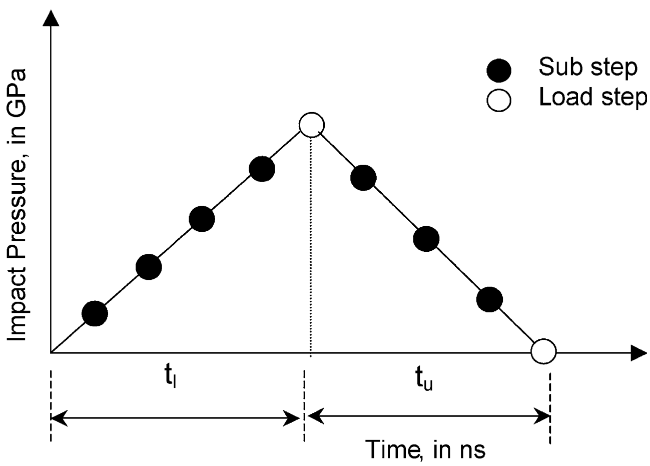

Fig. 7. Ramp loading.

't_l' and releasing the same over a duration of 't_u', i.e. unloading time, the residual stresses induced on the material were analyzed.

3. Results and discussion

3.1. Validation of the proposed model

In order to validate the proposed model, the results predicted with the proposed model are compared with those predicted by the approach proposed by Daniewicz and Cummings [5]. For this purpose, the approach proposed by Daniewicz and Cummings was implemented by considering the stationary pressure distribution, which is given by

$$\frac{P_S}{P_0} = \left[2\left(\frac{r}{r^*}\right)^3 - 3\left(\frac{r}{r^*}\right)^2 + 1\right] \quad (15)$$

where P_s is the stationary pressure and P_0 is the stagnation pressure of water, respectively.

The region of $7.5 \times 7.5 \times 2.5$ mm on 1100-H14 aluminium alloy was considered for analysis. A stationary pressure distribution corresponding to a water jet pressure of 140 MPa delivered from a nozzle bore diameter of 0.076 mm was applied over the region of analysis. Different mechanical properties of this material are:

Material : 1100-H14 Aluminium alloy	
Young's modulus, E (GPa)	69
Poisson's ratio (v)	0.33
Tangent modulus, E_t (GPa)	1.38
Yield stress, σ_y (MPa)	55
Density ρ, (Kg/m^3)	2700

Based on the limit on the Weber number of 52, a droplet radius of 0.125 mm was considered. Daniewicz and Cummings [5] considered the response of material to be bilinear plasticity, represented by two slopes. In view of small strains exerted by the water jets on the surface, the material is assumed to undergo kinematic strain hardening. Residual stresses induced on the surface and subsurface were obtained from the finite element analysis.

For the purpose of comparing the stresses induced on the material with the proposed approach, a jet pressure of 140 MPa, delivered from a nozzle of 0.076 mm diameter, was considered for transient dynamic analysis of the process. By employing the relations given in the Eq. (9), the average exit velocity of droplets was determined assuming the maximum velocity (u_{max}) of water droplet as 465.65 m/s. Impact pressure (P_{imp}) and impact duration (t_l) of droplets were determined with Eq. (10) and Eq. (13). Thus, an impact pressure (P_{imp}) of 1.01×10^9 Pa was applied for a duration of 2.89×10^{-9} s over the region of consideration.

Fig. 8 shows the variation of residual stresses in the radial direction by applying stationary and impact pressures over the surface. From this, it can be seen that both stationary and impact pressures induced compressive residual stresses on the surface. The magnitude of compressive stresses induced with stationary pressure is slightly higher than that induced with impact pressure. But, the extent over which the compressive residual stresses are induced with stationary pressures is less, i.e. 0.4 (r/r^*). In contrast to this, the application of impact pressures due to droplets induced compressive residual stresses over a larger region of 0.8 (r/r^*). This is in fact double the region of coverage that was noticed with stationary pressure distribution. Thus, this analysis clearly shows a definite advantage of

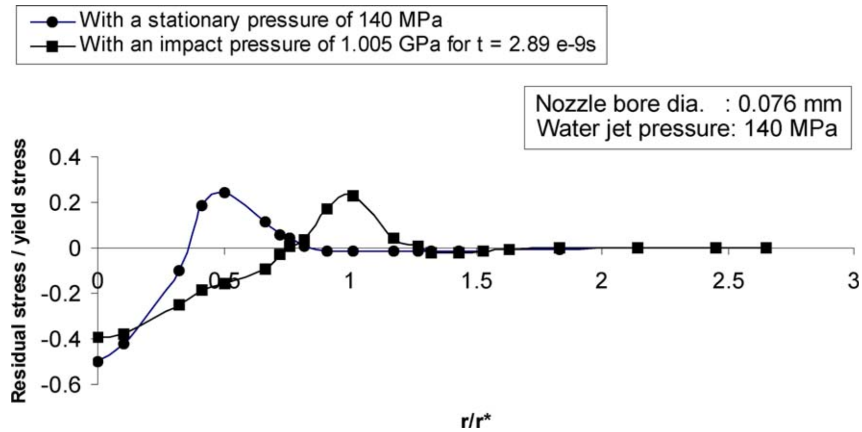

Fig. 8. Variation of residual stresses on the surface in radial direction.

proposed approach for predicting the residual stresses on the surface.

In Fig. 9, the variation of residual stresses predicted along the depth of material by considering stationary pressure distribution acting for a particular duration and impact pressures applied in a transient manner over the duration of impact. With the application of stationary pressure over the surface, the compressive residual stresses are limited to a depth of 0.08 (z/r^*). In contrast to this, the application of impact pressures due to droplets showed a different trend. The stresses predicted on the surface and subsurface layers are compressive in nature and are extended up to a depth of 3.5 (z/r^*). Such trend is definitely beneficial over the trend noticed with the application of stagnation pressures. This particular trend can be attributed to the following. Impact of water droplets causes spreading of water droplets thus increasing the contact periphery of the droplet and reducing the depth of compressive residual stresses on the surface by surface tension. A similar phenomenon was observed with deformable shots that have reduced the compressive stresses on the surface and increased them in the subsurface layers [9]. By increasing the size of droplet radius, the magnitude of compressive residual stresses was increased and the depth of compressive residual stresses was decreased on the subsurface. A similar phenomenon was observed with different aspect ratio of the shots, which have decreased the compressive residual stresses in the subsurface [8].

3.2. Experimental validation

For assessing the practical relevance of the proposed model, the results predicted with the model are compared with experimental results obtained by peening Aluminium 6063-T6 alloy using a round nozzle of bore diameter 1.2 mm. Aluminium 6063-T6 alloy, having an yield stress of 110 MPa, was considered for finite element analysis of water jet peened surface with jet pressure of 175 MPa. It produced an impact pressure of 1.295 GPa for a duration of 1.5×10^{-8} s. The impact pressure of droplets at different locations on the surface along with their duration of impact are

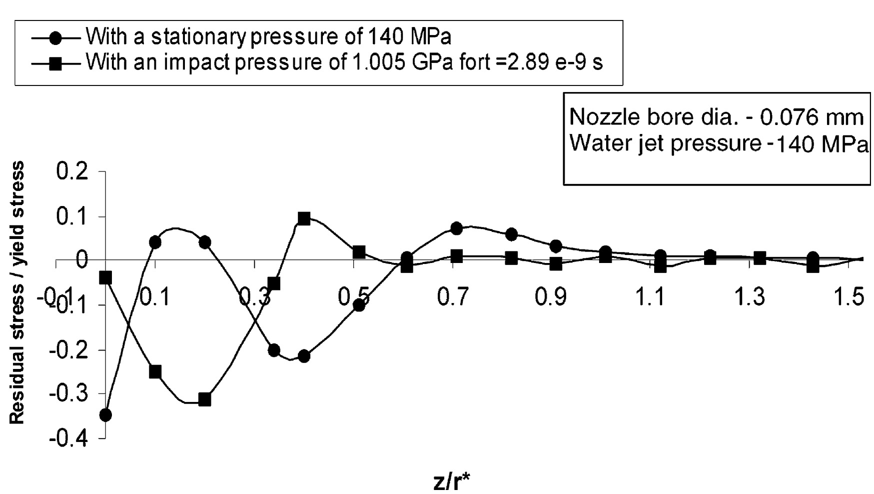

Fig. 9. Variation of residual stresses on the subsurface in axial direction.

Table 1
Pattern of loading on the surface modelled using transient dynamic finite element analysis: (water jet pressure: 175 MPa)

Sl. No.	Location of droplet from the axis of jet (μm)	Average exit velocity of droplet (m/s)	Shock velocity of droplet (C_1) (m/s)	Impact pressure (P_{imp}) (GPa)	Impact duration (t_{imp}) (ns)
1	62.5	512.94	2525	1.30×10^9	1.51×10^{-8}
2	187.5	481.36	2462	1.19×10^9	1.49×10^{-8}
3	312.5	438.07	2376	1.04×10^9	1.45×10^{-8}
4	437.5	387.75	2275	8.82×10^8	1.40×10^{-8}
5	562.5	333.44	2166	7.22×10^8	1.33×10^{-8}
6	687.5	277.55	2055	5.70×10^8	1.23×10^{-8}
7	812.5	222.21	1944	4.32×10^8	1.10×10^{-8}

estimated using the relations given by the Eqs. (10) and (13) and are presented in Table 1.

In order to illustrate the influence of jet pressure on stresses induced on the surface treated with water jets, different jet pressures such as 200 and 225 MPa were considered. By considering these pressures, the proposed model predicted the variation of residual stresses along the radial and axial directions and the results are shown in Fig. 10 and Fig. 11. For the purpose of validating the proposed model, the same material was treated with water jets by employing the same jet pressures. The residual stresses induced on the surface were measured by X-ray diffraction technique. This technique is used which can directly measure the interplanar

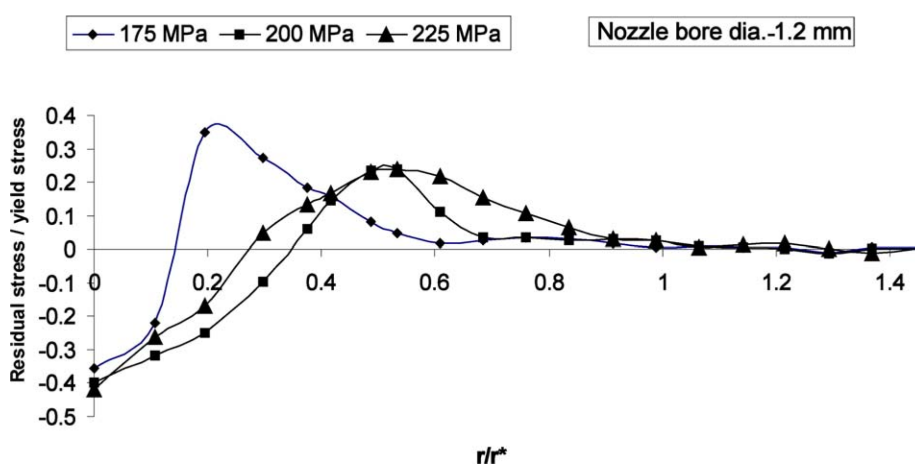

Fig. 10. Variation of residual stresses on the surface in radial direction.

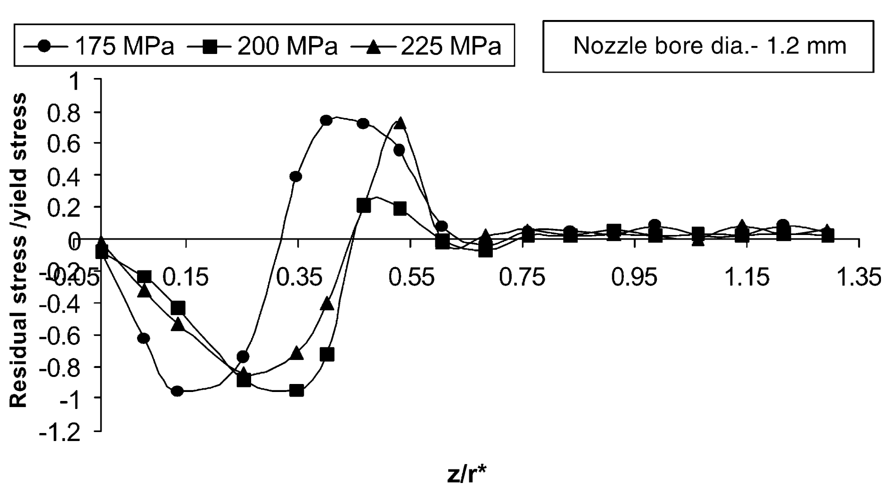

Fig. 11. Variation of residual stresses on the subsurface in axial direction.

Table 2
Comparison of experimental and predicted residual stresses on water-peened surface

Sl. No.	Water jet pressure (MPa)	Residual stress (MPa)		Percentage of deviation (%)
		Experimental	Predicted	
1	175	−37	−39.2	5.9
2	200	−45	−44.6	2.2
3	225	−42	−46	9.5

atomic spacing from which macro stress can be measured. Since this particular technique can measure the residual stresses induced on the surface, the comparison was limited only to surface stresses. From the experimental results, it was noticed that maximum compressive residual stress of 37 MPa was induced on the surface with a jet pressure of 175 MPa and a peening duration of approximately 7 s. With jet pressure of 200 MPa and peening duration of 7 s, these compressive stresses are seen to be 45 MPa. When the specimen was treated with a jet pressure of 225 MPa for a duration of 7 s, the compressive stresses induced on the surface were 42 MPa [12]. Table 2 shows the compressive stresses measured on the surface and the stresses predicted with the proposed model. From these results, it is evident that the proposed model can predict the stresses to an accuracy of 10%. From these results presented in Fig. 10 and Fig. 11, one can draw the following conclusions. By increasing the water jet pressure, the impact pressures increase which in turn can extend the region of compressive residual stresses on the surface and in the subsurface. However, enough care needs to be exercised to locate the specimen in the droplet region so that erosion of material with water jets can be avoided.

4. Conclusions

The proposed approach considered transient dynamic finite element analysis, for predicting the residual stresses on material treated with high velocity water droplets. Impact nature of droplets was simulated by applying impact pressures over a very short duration, estimated using Reichardt's theory and liquid impact theory. The effectiveness of the proposed model was shown by comparing the predicted stresses with those predicted by applying stationary pressure, based on the approach proposed by Daniewicz and Cummings [5], and with experimental results. The proposed model is found to predict the surface stresses to an accuracy of 10%. Analysis of results clearly indicated the effectiveness of proposed model for accurate prediction of compressive residual stresses on the surface. The magnitude of compressive stresses induced with stationary pressure is slightly higher than that induced with impact pressure. But, the extent over which the compressive stresses are induced with stationary pressure is less. In contrast to this, the application of impact pressures due to droplets induced compressive stresses over a larger region thus indicating the suitability of proposed approach for accurate prediction of the region of coverage and the magnitude of residual stresses on water peened surface.

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