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COMPRESSIVE RESIDUAL STRESS GENERATED BY BRISTLE BLASTING PROCESS WITH IMPLICATION UPON SCC. [1]

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ABSTRACT

Surface preparation tools/media are routinely used for removing corrosive layers and generating a receptive anchor profile for paints and coatings. At the same time, however, these tools inevitably generate a plastically deformed sub-layer that can alter the ability of metallic components to endure loads and resist failure. Subsurface compressive residual stresses, for example, are known to enhance life and thwart stress-corrosion cracking (SCC).

This technical paper focuses on process-induced residual stresses that are generated by commonly used surface preparation tools. In particular, the paper highlights an ongoing research effort that is aimed at modeling and analyzing the subsurface stresses that are generated during bristle blasting processes. A research program is outlined that focuses on assessing the plastic deformation imparted to steel surfaces, and the compressive residual stress state that is generated by repetitious bristle impact. Also, recent and ongoing studies are briefly outlined that examine the role that tool design and tool operating parameters play in surface-indentation mechanics and the formation of the depth of a worked layer. In addition, a comparison of process-induced residual stress state is made among bristle blast, grit blast, and coated abrasives tools, along with any implications that may affect surface integrity, fatigue life, and stress corrosion cracking (SCC).

BACKGROUND

The life-cycle of all load-bearing components is closely linked to the in-situ performance of their surfaces. This simple truth has given rise to a litany of terminology that attempts to capture a broad spectrum of surface engineering processes that have evolved over time. While some may argue that commonly used categorization schemes such as surface *finishing, conditioning, preparation,* and *treatment*, are discrete, specialized processes, they are more likely inseparable. Consider, for example, the broad family of mechanical tools and processes that are used for cleaning and profiling metallic surfaces:

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■ Crater-based/Micro-indentation Processes
    Grit blast
    Bristle blast/Wire bristle impact[2]
    Needle gun
    Rotary Flap
    Miscellaneous: Cutter bundles; certain Flail devices, etc.

■ Sliding Contact/Striation-based Processes
    Grinding discs
    Coated abrasives
    Non-woven abrasives
    Flap, filamentary, wire brushes, etc.

At first glance, the above categorization scheme (i.e., *crater/indentation* and *sliding/striation*) may also appear to be one of convenience; however, a closer look at these fundamentally different processes will reveal important distinctions.

■ <u>Crater-based/Micro-indentation Processes</u>

Tools and processes cited in this category are based upon principles of (localized) impact, and the ensuing formation of craterlike micro-indentations that are generated on metallic surfaces. Their brief contact with the surface (i.e., $\approx 10^{-3}$ sec) generates little/immeasurable frictional heating, and yet creates (in aggregate) a morphology or "anchor profile" that is deemed essential for the subsequent adhesion and stability of applied protective coatings. At the same time, each impact event is associated with surface fragmentation, which provides the basis for both the removal of surface rust/contaminants, and the eventual exposure of newly generated base-metal. The ability of these processes to simultaneously clean and profile the surface has made them an attractive option in the surface preparation community. In addition, the engineering community has additional purpose for favoring these processes; that is, these processes can simultaneously generate compressive residual stress to a significant subsurface depth, which is vital for enhancing component life and for delaying the onset of stress corrosion cracking (SCC). Although some information has been published on the residual stress state formed via grit blast processes, little or no scholarly research has been published that examines the residual stress state that is characteristic of the remaining processes cited in this list.

■ <u>Sliding Contact/Striation-based Processes</u>

Tools that have been placed in this category are based upon the formation of score markings or "striations" that are generated during the material removal process. Grinding discs, for example, utilize sharp, hard particles that are bonded to the face of rotary or oscillatory tools which, in turn, cut/plow through surface debris and base metal. This extended duration of sliding contact between the media and metallic surface results in rapid material removal rates, frictional heating, and the eventual exposure of a cleaned base metal. Often, the surface texture/morphology that is generated by these tools can lack the profile requirements that are specified for paints/coatings. Consequently, further surface treatment (frequently, impact/crater-based processes) must be used for completing the task.

In some cases, frictional heating that is induced into the workpart surface can pose a serious problem. That is, high temperatures generated along the surface and within the substrate are known to create extreme tensile residual tensile stresses which, in turn, reduce component life and increase susceptibility to SCC[1-3]. In extreme cases, surface burn marks/discoloration (termed *grinding burn*) can be visually detected, which is an oxidized layer that may be accompanied by the formation of surface cracks and metallurgical transformation   This form of thermo-mechanical damage frequently arises when excessive force is applied to the tool, and/or when the cutting action of media is thwarted. In such cases, the application of greater tool force

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[2] This is the latest, or most recently developed tool that has been added to the wide assortment of surface finishing tools.

increases the material removal rate and worker productivity, along with the likelihood of imparting severe thermal damage to the surface.

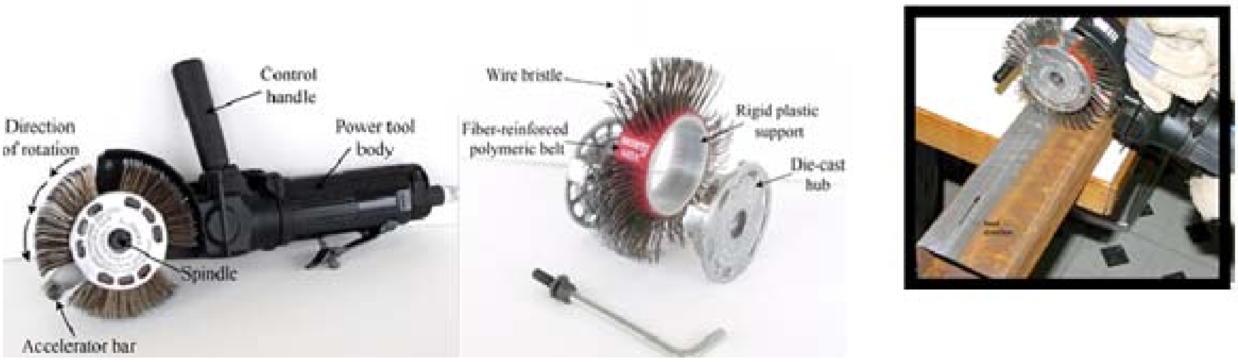
In summary, excessive tool force and grinding burn must be avoided, even though this may increase worker throughput. Despite widespread publicity of this important concern in the engineering literature, a cursory review of Steel Structures Painting Council (SSPC) literature (Surface Preparation Specification 11: *Power-Tool Cleaning to Bare Metal*) has shown that no instructional or cautionary statements regarding this hazard have been issued to the surface preparation community. This absence of technical information both thwarts best-training practices and places unnecessary risk for premature coating and/or component failure.

BRISTLE BLASTING PROCESS AND FORMATION OF RESIDUAL STRESS

The purpose of this technical paper is to provide a brief description of the bristle blasting process along with an explanation of the mechanical surface interactions that are characteristic of the process. Specifically, the paper will focus on the material removal performance and the surface/subsurface layer that is generated during the cleaning and profiling process. Experimentally obtained residual stresses that are formed in the sub-layer will be presented and discussed, along with preliminary results outlining an effort that is aimed at modeling the impact and micro-indentation process.

Power Tool Description and Mechanical Principle of Operation

The most common adaptation of the bristle blaster is shown in Figure 1a and 1b, and consists of a rotary tool which is attached to – and driven by - pneumatic or electric motor. Use of the tool during a typical application (see inset) indicates that longitudinal overlapping bands are repeated along the surface until complete coverage is obtained.



(a) (b)

Figure 1 (a, b) Components of hand operated bristle blasting power tool, and (inset) illustrating tool use during a typical cleaning application.

The impact and subsequent rebound of bristle tips occurs very rapidly, and is depicted in Figure 2 with the aid of a high-speed digital camera. One may observe that the sequential movement of the bristle clearly illustrates the oncoming motion of the wire (pre-impact frame 1), impact (frame 2, highlighted), and subsequent rebound/retraction (frames 3-5) of the wire bristle. A typical crater that has been formed by bristle tip impact is also shown in Fig. 2 (see inset, top right).

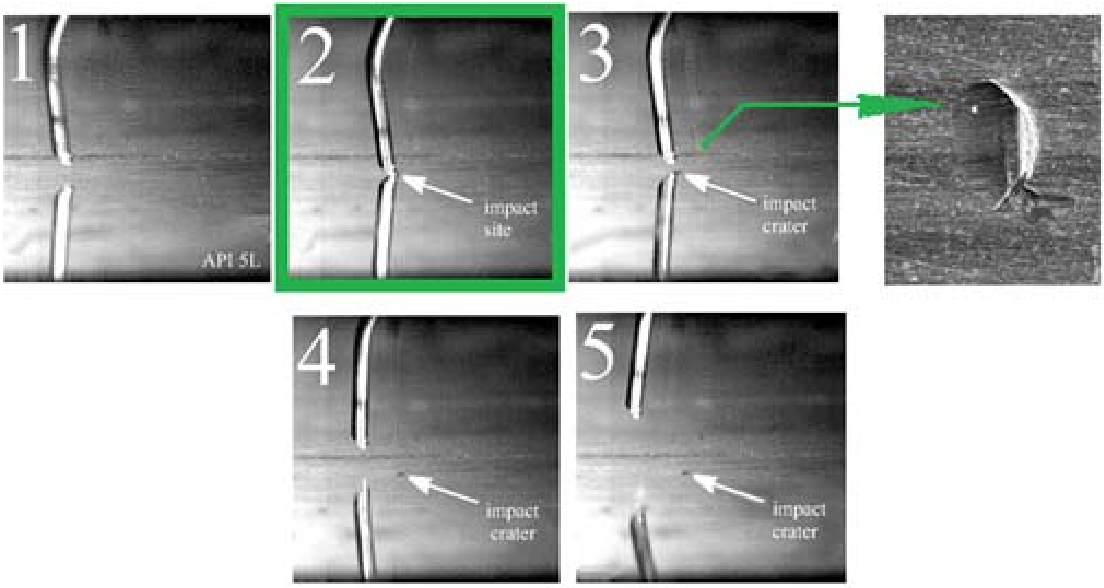
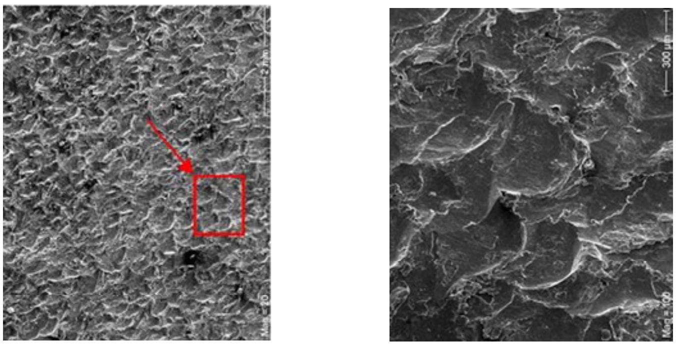


Figure 2: Five consecutive frames captured from a high-speed digital camera depicting the approach of the bristle tip (Frame [1]); impact (Frame [2]); retraction (Frames [3-5]).

During ordinary use of the fully populated tool, thousands of craters are generated each second, and the final outcome of a cleaned and textured surface is Figure 3a. In Figure 3b the surface (see red arrow) is shown at somewhat higher magnification, whereby one can clearly detect the individual impact craters that constitute the surface profile.

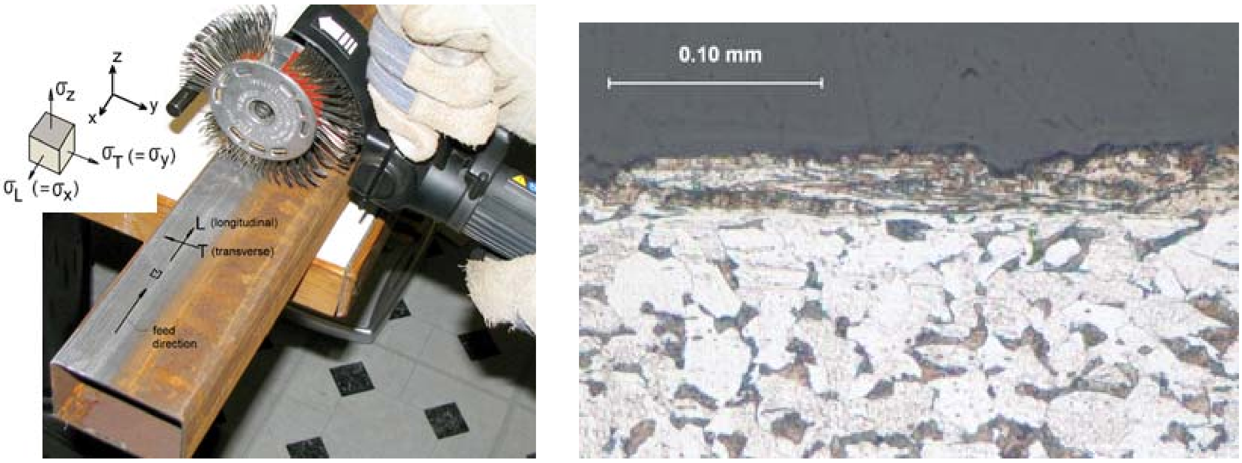


(a) **(b)**

Figure 3 (a) Scanning electron micrographs of the bristle blast treated surface shown at 20x, and (3b) at 100X for region indicated by the red arrow. Surface/Subsurface Residual Stresses Generated by Bristle Blast Process

Residual Stresses Generated by Bristle Blasting Process

Figure 4a depicts use of the bristle blasting process for a corrosion removal application, and establishes the longitudinal and transverse coordinate directions, which will be used for identifying the stress components σ_x and (σ_y), respectively. The cross- section micrograph shown is Figure 4b identifies the worked layer (top region) that extends approximately 30 microns below the surface, followed by an undisturbed substrate (material: ABS-A steel).



(a) **(b)**

Figure 4: (a) Illustration of bristle blasting tool used for corrosion removal application. Feed direction corresponds to longitudinal coordinate, whereas perpendicular direction corresponds to transverse coordinate; (b) cross sectional micrograph depicting worked layer and undisturbed substrate (ABS-A steel).

Results are shown in Figure 5 for the through-thickness residual stresses that have been formed in ABS-A steel via the bristle blasting process. These results (obtained using x-ray diffraction) indicate that significant compressive residual stresses are generated at and below the surface to a depth of nearly 250 microns. Both the longitudinal stress (σ_x) and transverse stress (σ_y) follow a similar pattern, reaching greatest compressive residual stress within the vicinity of 30-50 microns.

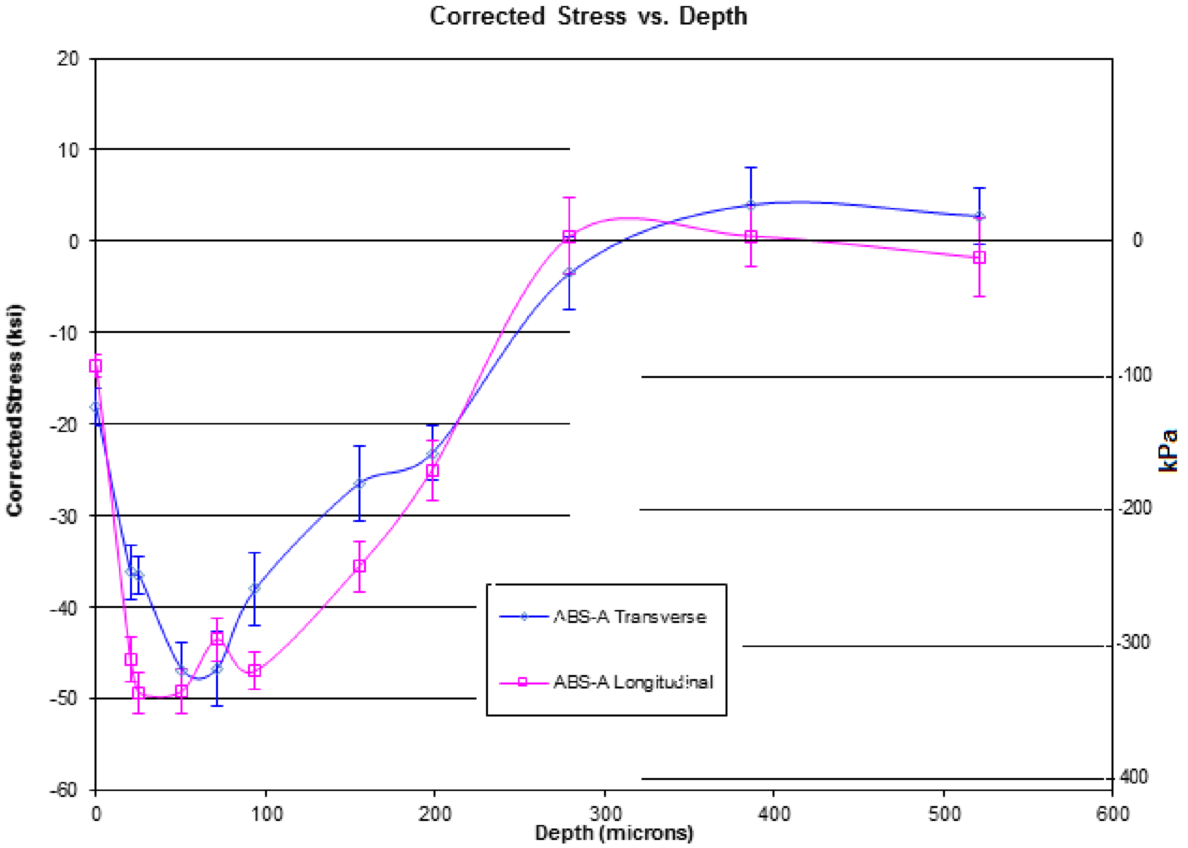


Figure 5 Residual stresses measured using x-ray diffraction for ABS-A bristle blast surface.

These results are intriguing, and suggest that stresses generated during the bristle blasting process can have a marked effect on prolonging the life of structural components as well as postponing failure associated with SCC.

MODELING AND ANALYSIS OF BRISTLE BLASTING PROCESS

Mechanics Formulation and Preliminary Discussion

Repeated laboratory observations of high-speed digital time-lapse imagery suggest that filaments remain approximately straight-sided (i.e., exhibit little flexure) throughout the impact process. This observation suggests that rigid body mechanics is a viable candidate for evaluating the bristle/workpart collision process. To this end, a research effort has been undertaken that will provide insight into the impulsive load that arises at the interface of the bristle tip/workpart surface.

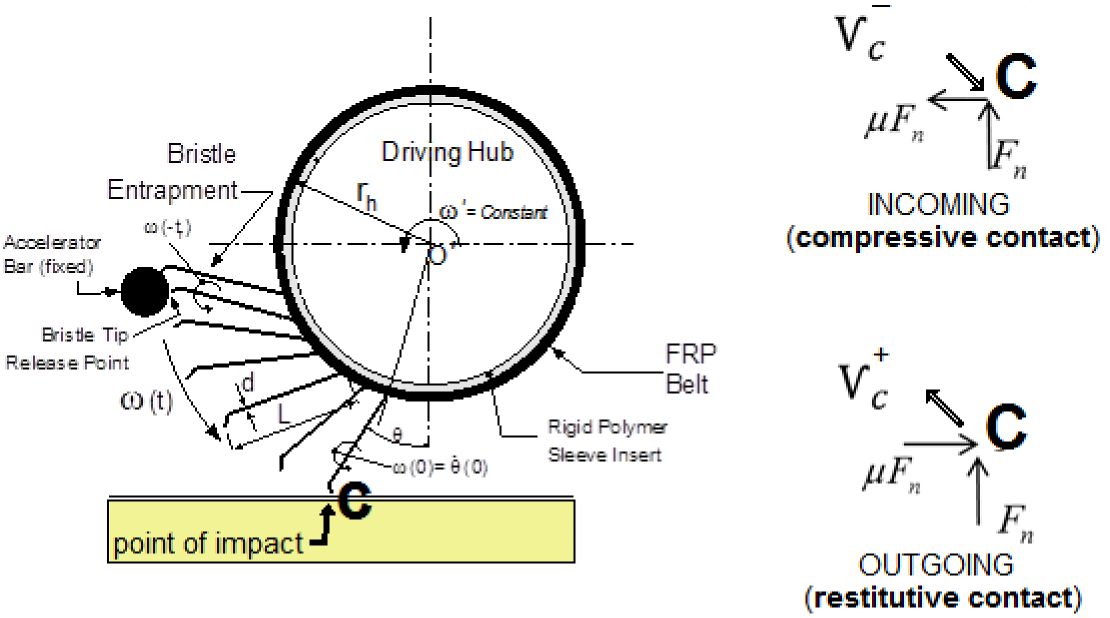


Figure 6 (left) Illustration of essential features for the bristle blasting process, including (top right) incoming and (bottom right) outgoing velocity along with the associated force systems.

Key features of the overall problem are shown in Figure 6 whereby, upon release from the accelerator bar, the bristle gains speed and strikes the target surface with pre-impact speed v^-, and retracts with rebound speed v^+. Mathematical formulation of the problem is based upon the impact mechanics of a single wire bristle that imparts frictional contact during the collision to the surface at point C. Details concerning an energy-impulse formulation have been discussed by Stronge[4,5] for a closely related problem, and only a brief summary is provided below within the context of the current problem.

As outlined in ref.[5], an energy-impulse integral equation can be readily formulated for modeling both compressive and restitutive rigid-body impact in conjunction with frictional contact as follows:

$$\int d\left(\frac{\partial T}{\partial \dot{\theta}}\right) = d\pi = \int_0^{p_c} d\bar{p} \cdot \frac{\partial \bar{V}}{\partial \dot{\theta}} \qquad (1)$$

where T is the bristle kinetic energy, p is the impulse, V is the bristle tip resultant speed, and $\dot{\theta}$ is the angular speed (rad/sec) of the bristle. Normal component of the work done during compressive impact is computed on the basis of Eq. (2) as follows:

$$W(p_c) = \int_0^{p_c} V(p)\,dp \qquad (2)$$

whereas the (net) work $W(p_r)$ performed during contact restitution is evaluated:

$$W(p_r) = W(p_f) - W(p_c) = \int_{p_c}^{p} \bar{V}(p)dp \qquad (3)$$

where, in Eq. (3), $W(p_f)$ is the total work performed throughout the impact cycle. This facilitates computation of filament rebound angular speed $\dot{\theta}_f$ via the following result:

$$\frac{\dot{\theta}_f}{\dot{\theta}_0} = \frac{\dot{\theta}(p_f)}{\dot{\theta}(0)} = \frac{\frac{b_4}{ma_3}(p_f - p_c)}{\frac{a_4}{ma_3}(p_c)} \qquad (4)$$

where $\dot{\theta}_o$ [=$\dot{\theta}(0)$] is the initial (i.e., incoming) bristle angular speed (rad/sec), m is the bristle mass(kg), and b_4, a_4, a_3 are undisclosed constants that are peculiar to the current bristle impact problem[4].

Preliminary Numerical Results

The normal component of the *compressive work* performed on the target surface (i.e., Eq. 2) during compressive contact has been recently computed for an actual single bristle whose dynamic properties have been carefully evaluated, and are shown in Figures 7a and 7b. Numerical values chosen for the impact friction coefficient μ (i.e., 0 ≤ μ ≤ 1) are speculative, as no data is yet available for this impact parameter.

Work performed by the normal impulse load during compression is shown in Fig. (7a) and indicates that at greater angles of bristle inclination (i.e., larger impact angle θ shown in Fig. 6) increased work is performed. At the same time, one may conjecture that greater/steeper angles of impact can lead to or promote greater (compressive) residual stresses on and within the target surface. Furthermore, it may be readily argued that this result is consistent on the basis of physical considerations; that is, steep impact angles indeed give rise to a greater component of bristle tip velocity along the *perpendicular* (i.e., *normal*) direction which, in turn, implies increased kinetic energy is available for transfer from the bristle tip to the target surface.

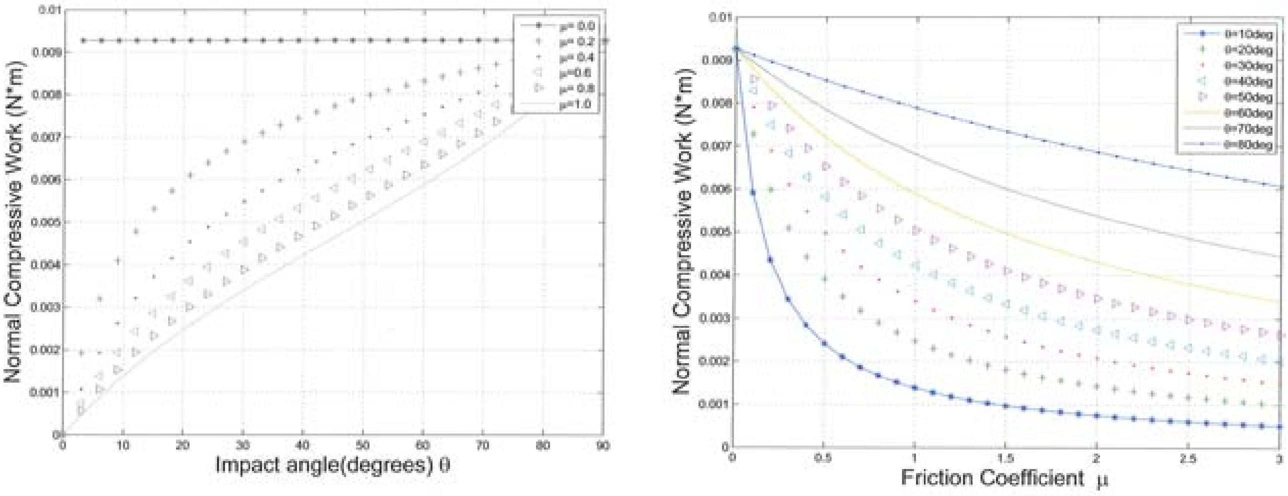


Figure 7: (a) work performed by normal impulsive load during contact for various angles of inclination θ, and (b) work performed by normal impulsive load during contact for various hypothetical values of friction coefficient μ.

However, the practical range of contact angles that are used during bristle blasting operations has been carefully measured, and typically varies from θ =15° (shallow workpart penetration) to θ

= 30^o (deep workpart penetration). This practical matter would therefore, preclude the use of Fig. 7a beyond the range of $\theta = 30^o$.

Finally, in Fig. (7b) one may observe that increased impact friction coefficient μ leads to decreased work performed by the normal impulse load, indicating that as expected, energy is lost to frictional forces that are generated between the bristle tip and target surface during impact. However, the nature and magnitude of the impact friction coefficient that is generated during the bristle blasting process is not yet available at this writing.

SUMMARY

Discussion presented in this paper has purported that bristle blasting is a most viable process for both cleaning and simultaneously generating an anchor profile that rivals grit blasting processes. Also, preliminary results that have been reported for residual stresses generated during bristle blasting operations indicate that significant compressive residual stresses are generated at and below the surface to a depth of nearly 250 microns. This finding is significant, as such a residual stress pattern can promote resistance to crack growth, improved fatigue life, and improved resistance to SCC.

In addition, a mechanics-based formulation has been briefly outlined that can be used for modeling rigid-body bristle tip impact, which includes frictional contact with a target surface. The normal component of the *compressive work* performed on the target surface has been computed for an actual single bristle whose dynamic properties coincide with those that constitute the bristle blasting tool. These results can provide insight into the role that tool operating conditions and workpart surface friction can play in generating compressive residual stresses, which are of paramount importance for postponing failure associated with SCC.

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