Development of *Bristle Blasting Tool* for Cleaning and Preparation of Metallic Surfaces

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In this article, a new method for stripping and preparing metallic surfaces is introduced, namely, rotary ***bristle blasting***. The method derives its name from three features that uniquely characterize the process. First, the rotating bristle tips that impact the surface are comprised of sharp, hardened steel wire, and are designed to strike the workpiece surface with kinetic energy that is consistent with abrasive blast media. Second, the bristle tips strike the surface with sufficient impulse to cause an abrupt collision and rebound, similar to that observed by traditional abrasive blasting processes. Third, the bristle tips are continuously re-sharpened as they move through a protective shroud that partially encloses the rotary tool. Consequently, the bristle tips remain sharp throughout the life of the tool and offer constant performance for both removal of the coating and imparting a desired texture to the metallic surface. This technical paper also examines key issues regarding the design of the bristle blasting tools. Moreover, performance of the bristle blasting tool is assessed by direct use of the Steel Structures Painting Council (SSPC) standards. That is, the initial condition of steel surfaces upon which scale or corrosion has formed are examined and categorized in accordance with SSPC visual standards and procedures. Subsequently, the corroded surfaces are treated by the bristle blasting tool, and compared with those prepared by both existing power tools and dry abrasive blast cleaning. The results obtained indicate that single-step use of bristle blasting tools can achieve bare metal, textured surfaces that heretofore have been associated with traditional abrasive blast cleaning processes.

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Introduction

Metallic components are manufactured by a host of machining and forming processes, such as milling, turning, rolling, forging and extruding operations. In each case, the newly-generated surfaces are prone to contamination and corrosion, which ultimately must be removed prior to the application of sealants, paints, and coatings. Also, surfaces that have been previously treated with protective coatings must be periodically refurbished, which involves the removal of defunct scale prior to applying new coatings. Thus, maintenance engineers are constantly in search of cleaning and stripping processes that are cost-efficient, user-friendly, and have minimal adverse environmental impact.

In order to satisfy these stringent criteria, several mechanical surface preparation methods have risen to the forefront, such as wire brushing, abrasive sanding, and abrasive blasting. In a production environment, however, the method chosen for performing the surface preparation task must exhibit consistent performance for extended periods of use. That is, process control must remain stable throughout the operation, thereby minimizing downtime as well as the potential for unacceptable and/or variable operator performance. Two of the previously cited surface preparation methods, namely, wire brushing and abrasive sanding, suffer from significant disadvantages in this regard. The performance of wire brushes, for example, can vary significantly within a relatively short time period. That is, although the bristle tips are initially sharp and, thus, exhibit aggressive machining performance, continued use of the brush leads to the inevitable progressive wear of wire tips. Consequently, the quality and consistency of the machined surface rapidly deteriorates, and eventually renders the tool inadequate for further use. Likewise, abrasive sanding tools are prone to similar performance variations. In this case, the initially sharp edges of the cutting mineral (silicon carbide, aluminum oxide, etc.) become “capped” or coated by trace materials of the parent workpart that is being machined. In short order, the machining capability of the tool deteriorates, and results in poor material removal performance and increased frictional heating of the workpart.

Unlike wire brushing and abrasive sanding, the abrasive blasting process can readily avoid such material removal performance variations. As shown in Figure 1, this process uses a reservoir of abrasive media which is metered from a pressurized containment vessel, and propelled toward the workpart surface via a hose/nozzle system. A well-trained operator is capable of regulating the critical process parameters so as to obtain the desired surface cleanliness and texture that is required for the application. Thus, performance variations are minimized or eliminated because the size, shape, and composition of the blast media are approximately homogeneous, and available in unlimited supply.

Although abrasive blasting is the most widely used method for surface preparation/contractor applications, several drawbacks can be identified that significantly detract from its implementation. These are briefly summarized as follows:

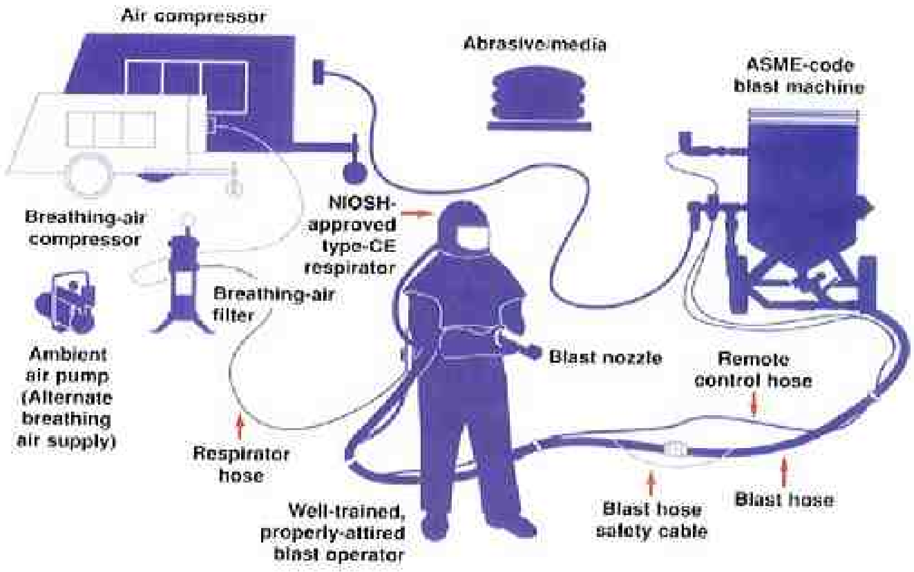

Figure 1 Overview of various apparatus and safety equipment needed for performing abrasive blasting operation (Source: Roman, P., Taking Care of Abrasive Blasting Equipment, Journal of Protective Coatings and Linings, p. 19, August, 2004)

1. Abrasive blast machines and their supporting equipment (reference Figure 1) are inherently complex and cumbersome, and require significant investment in capital equipment. Moreover, the equipment must be regularly maintained and/or replaced in order to ensure reliable and acceptable performance.
2. Due to the high concentration of environmental debris and air-borne contaminants, the operator must don specially designed protective gear and ventilating equipment. Consequently, operator comfort is compromised, leading to fatigue and frequent turnover of trained personnel.
3. The apparatus must be used in a well-contained or closed system. That is, the escapement of debris and air-borne contaminants must be restricted, and the blast media must generally be recovered for reuse in future applications. Consequently, abrasive blasting processes often require a dedicated work-space for carrying out the operation.

The above drawbacks indicate that there is a need to develop improved methods and alternative tools that can simplify and reduce the cost and safety hazards of abrasive blasting operations.

In this paper, a new method is proposed that can be used in lieu of abrasive blasting operations. This new approach utilizes a specially designed tool which is comprised of sparsely populated wire bristles having heat treated, hardened tips that are continuously sharpened during tool operation. Several details regarding the kinetic and kinematic design of the bristle blasting tool are discussed, and the dynamic performance of the tool is corroborated using a high-speed digital camera. Finally, the tool is used for removing corrosion from steel specimens that have been weathered in an unprotected atmospheric environment. The corrosion-removal performance of the tool is assessed on the basis of SSPC visual standards, and the texture/profile of prepared surfaces is measured and reported. The results of this work indicate that bristle blasting tools can offer an important option to the surface finishing community for safe, convenient, and cost efficient preparation of severely corroded metallic surfaces.

Elementary Design Considerations for Bristle Blasting Tools

Energy Equivalence of System

The starting point that is used for obtaining an approximate equivalence in performance between abrasive blast media and the rotary bristle blasting tool is based upon rigid body mechanics[1]. First, the kinetic energy of an *oncoming* particle of media, as shown in Figure 2a, is given by

$$(1)\quad KE^{p} = \frac{1}{2} m_p \cdot \left(v_p \cdot \sin\alpha\right)^2$$

where m_p is the particle mass, v_p is the particle translational velocity, and α is the incident angle of entry with respect to the smooth workpart surface. Next, the

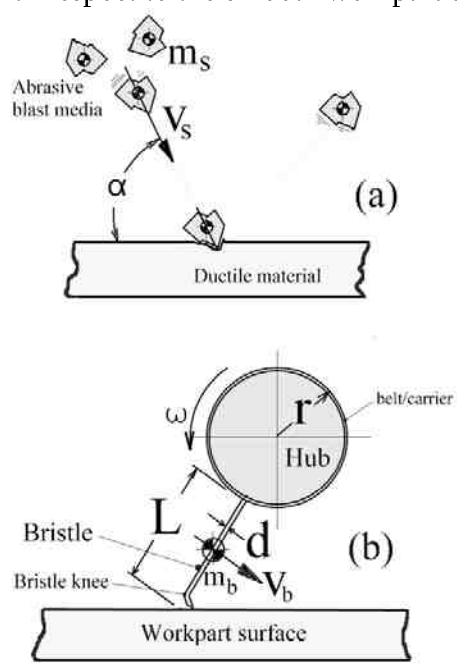

Figure 2 Illustration of (a) oncoming abrasive blast media and subsequent impact/plastic deformation of ductile workpart surface/surface, and (b) bristle attached to rotating hub at instant of impact

kinetic energy of a rotating bristle is likewise examined (Figure 2b) and is given by

$$(2) \quad KE^{b} = \frac{1}{2}\left(\frac{1}{12}m_b \cdot L^2\right)\cdot \omega^2 + \frac{1}{2}m_b \cdot v_b^2$$

where L is the approximate bristle length, m_b is the bristle mass, v_b is the velocity of the bristle mass center, and ω is the angular velocity of the rotating hub. The above simplification presupposes that the bristle is pin-connected at the hub and also presumes that all of the bristle kinetic energy (i.e., rotational and translational energy) is available for the impending impact. In the current problem, equivalence is sought between the two different expressions given in Eqs. (1) and (2). Thus, their direct equality leads to the energy-equivalent hub speed n

$$(3) \quad n = \frac{30 v_p}{\pi}\left[\sqrt{\frac{m_b}{m_p}\frac{\frac{1}{12}L^2 + \left(\frac{L}{2}+r\right)^2}{\sin^2\alpha}}\right]^{-1}$$

where r is the radius of the hub, and the standard relationship between angular velocity ω and the rotating speed n (rpm)

$$(4) \quad \omega = \frac{\pi}{30}n$$

has been used in Eq. 3. Inspection of Eq. (3) suggests that the hub speed of the bristle brush can be directly computed by choosing the size, material composition and nominal speed of the media as well as the candidate dimensions and material system that comprise the bristle/brush system. The measured speed of blast media that has been cited in the literature[2] ranges from 30m/s -110 m/s. Here, standard steel media (G16, approximately 1 mm diameter) with a nominal speed of v_p = 50 m/s and incident angle α = 70° is selected for the current problem, and a steel wire bristle will be driven on a hub having a radius of r = 28 mm. Presently, one may choose any standard wire diameter d, and length that is commensurate with the currently chosen hub and the final outcome that is desired for the texture of the treated workpart surface. In the current work, practical considerations have led to the selection of bristle dimensions L = 29 mm and d = 0.73 mm. Thus, the parameters m_b, and m_p, can be readily computed or directly measured. Direct measurement of these parameters leads to the approximate mass ratio $m_b/m_p \sim 10.0$ and thus, the corresponding brush rotational speed n = 3,230 rpm is obtained from Eq. (3).

Contact Mechanics: Bristle Impact and Rebound

As depicted in Figure 2a, the abrasive blasting process consists of an incoming stream of media which, upon colliding with the workpart surface, results in rebound of the particles and a multitude of impact craters. This repetitious action produces both material removal and plastic deformation of the ductile workpart surface/subsurface, and has been studied in detail by previous researchers[2-3]. Moreover, the texture and visual appearance of the treated surface is a direct consequence of the blast process, and plays a key role in assessing and preparing surfaces for subsequently applied paints and coatings[4-5]. It is conjectured, therefore, that the material removal performance and surface texture which is produced by abrasive blasting can be replicated by utilizing the dynamic properties of bristles. That is, contact of the bristle tip must be immediately followed by a *retraction* or *rebound* from the workpart surface, and score markings that are commonly associated with bristle tip sliding must be averted.

The feasibility of attaining an abrupt collision and rebound of a single bristle tip was first reported in 1993 by Shia, et al.[6], and was shortly thereafter observed using a strobe-video system[7]. More recently, researchers have reported experimental evidence of bristle tip rebound within the contact zone of a rotating (injection molded) brush by direct measurement of bristle contact forces using a specially designed workpart fixture and force sensor[8-9]. As a direct consequence of these recent findings, bristle peening tools with spherical tips that exhibit direct rebound have been designed, fabricated and used in a computer numerical-controlled (CNC) environment[10]. These findings have been made feasible, in part, by using a high speed digital camera (Photron® FASTCAM-Ultra APX-RX) that has the capability of resolving continuous motion within time frames as small as 1/120,000 sec. This same method of analysis has also been used in the design of a sharp-tip bristle brush that can meet or exceed the corrosion removal performance of abrasive blast processes. Further details regarding the design and performance of the bristle blasting tool are given in the forthcoming sections.

Design of Bristle Blast System

The overall design of a prototype bristle blasting system is shown in Figure 3, and consists of a hand-held power tool with two separate spindles that are driven by compressed air. The bristle blasting tool is attached to the primary spindle which rotates counterclockwise at approximately 3,750 rpm. At the same time, a sharpening tool comprised of a coated abrasive disk rotates on a secondary spindle at approximately 21,000 rpm in the clockwise direction. The distance between the bristle tip and the surface of the abrasive disk is readily adjusted, thereby providing either continuous or intermittent sharpening of the bristle tip. Thus, after the sharp bristle tip collides with the workpart surface, the geometry of the tip is restored/re-sharpened prior to the next cycle of contact.

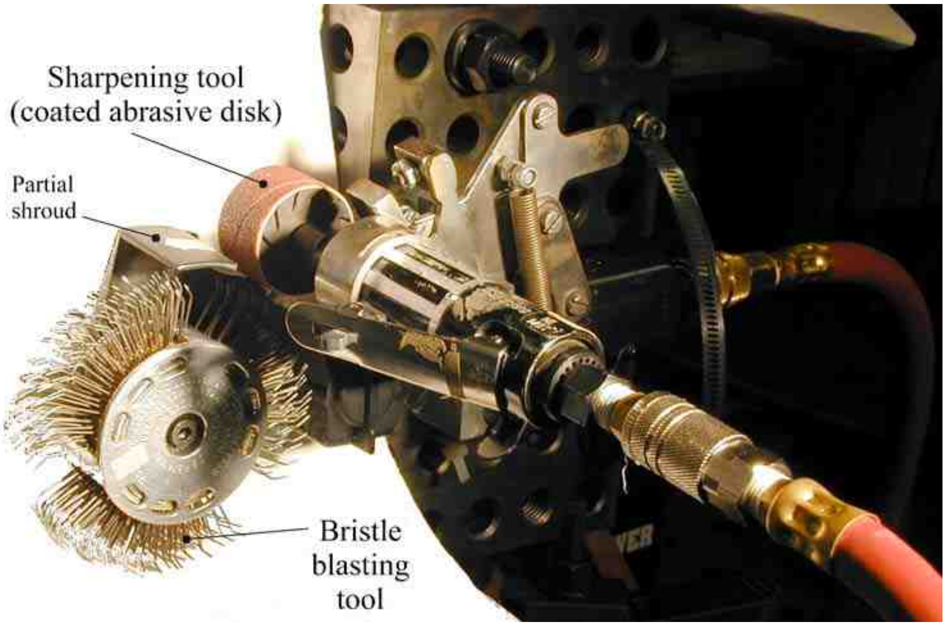

Figure 3   Photograph of prototype bristle blast system and associated fixture used for studying bristle dynamic performance via high speed digital photography

As previously noted, design of the bristle itself is, in part, carried out with information that is gathered by use of a high speed digital camera. As a starting point for the bristle design process, the dynamic response of a single bristle is evaluated. Subsequently, the bristle geometry is further optimized subject to the requirement that bristle tip impact is immediately followed by rebound/retraction of the tip from the workpart surface. Thus, the dynamic response of a candidate optimal bristle design is shown in Figure 4a,b,c, whereby three frames of motion acquired from the high speed camera are illustrated*. In this series of photographs, the single filament is operating at approximately 3,750 rpm, and contact is made with a light-reflective flat steel workpart surface. The frame shown in Figure 4a corresponds to the initial impact configuration of the bristle. Subsequently, the bristle tip rebounds from the workpart and reaches the maximum retracted height (above the workpart surface) shown in Figure 4b. Next, as shown in Figure 4c, the filament tip may return to the workpart surface, thereby causing a secondary impact. Nevertheless, the primary (i.e., initial) rebound is of key interest in designing the tool, as this feature must be retained when additional bristles are added to the tool.

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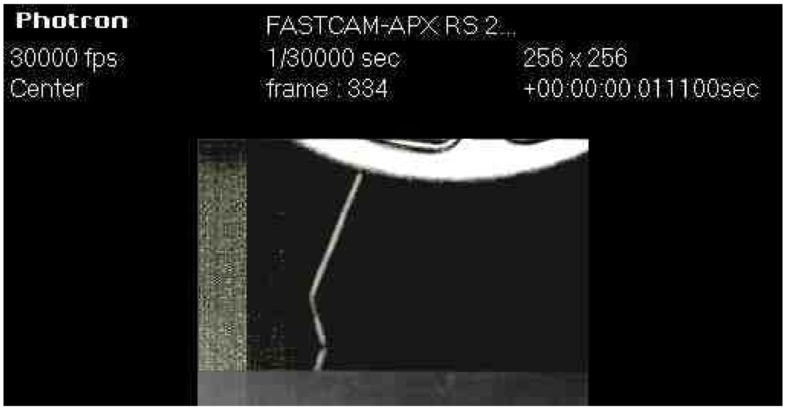
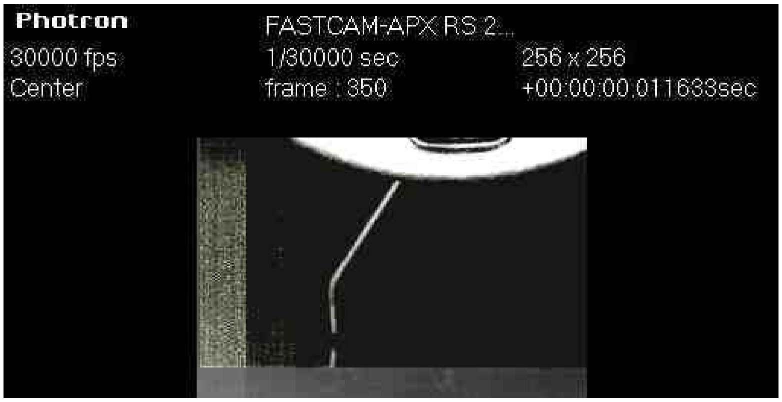
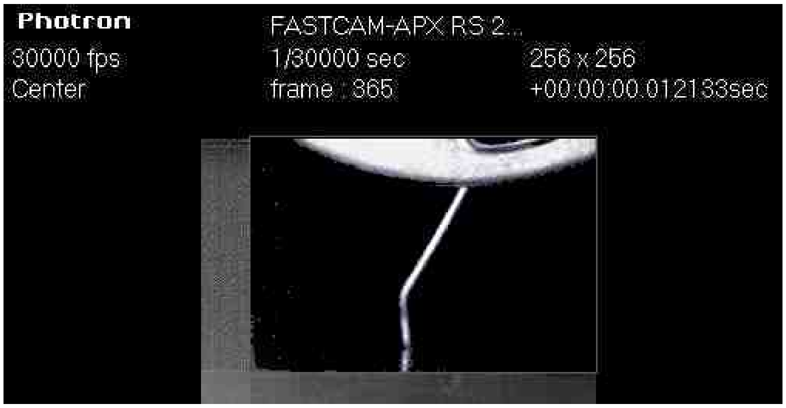
* Note: All high speed frame segments reported in this paper have utiliized a 1/30,000 sec. time duration.



(a)



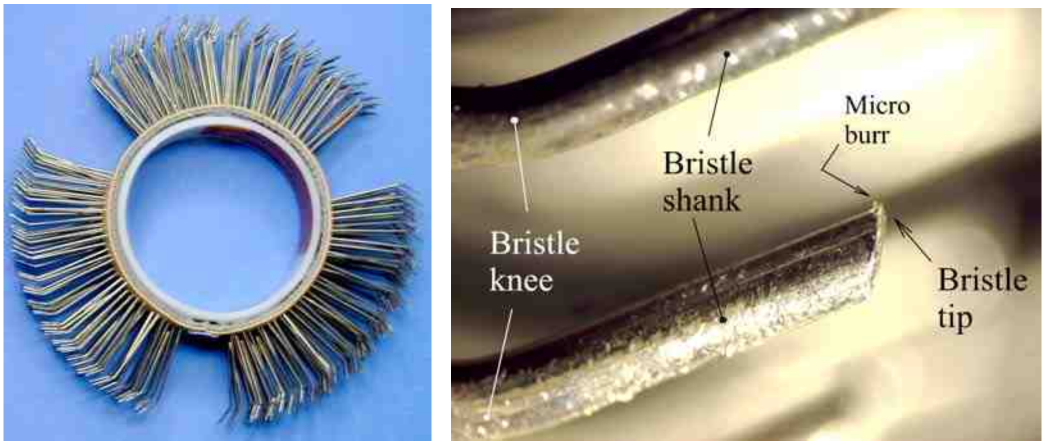
(b)



(c)

Figure 4 Three frames chosen from high speed digital camera to illustrate dynamic response of a wire bristle. Bristle is rotating in counterclockwise direction, and is shown at (a) initial point of contact (i.e., primary impact) along flat workpart surface, (b) maximum rebound height of bristle tip following primary impact, and (c) secondary impact with flat workpart surface

In Figure 5(a) the overall design and geometry of the populated bristle blasting tool is shown. The bristle design incorporates a knee, or *shank* that has been heat treated to the approximate Rockwell hardness $R_c = 62$. This portion of the tool is repeatedly refurbished/re-sharpened throughout the bristle blasting process. The photograph shown in Figure 5(b) illustrates the shank region of the bristle and depicts the re-sharpened tip after approximately 15 minutes of service. Here, a micro-burr associated with the re-sharpening process is clearly visible at the leading edge of the bristle, and the tip shape appears sharp with an acute angle



(a) (b)

Figure 5 (a) Photograph of bristle blasting tool that was designed, fabricated, and used in the present study, and (b) Shank portion of bristle, which corresponds to the region bounded by the knee and the bristle tip. This photograph shows the condition of the bristle tip after approximately 15 minutes of service. Micro-burr seen along the extreme edge of the bristle tip is a consequence of the continuous re-sharpening process during tool use.

of approximately 60°. In order to illustrate the dynamic response of this populated tool, a single frame of motion that was obtained during tool operation is shown in Figure 6. Playback and careful examination of this video stream indicates that each bristle tip clearly undergoes an impact and rebound within the initial portion of the contact zone. Nevertheless, this "still frame" shows that, upon initial contact, the bristle tips abruptly rebound from the workpart surface.

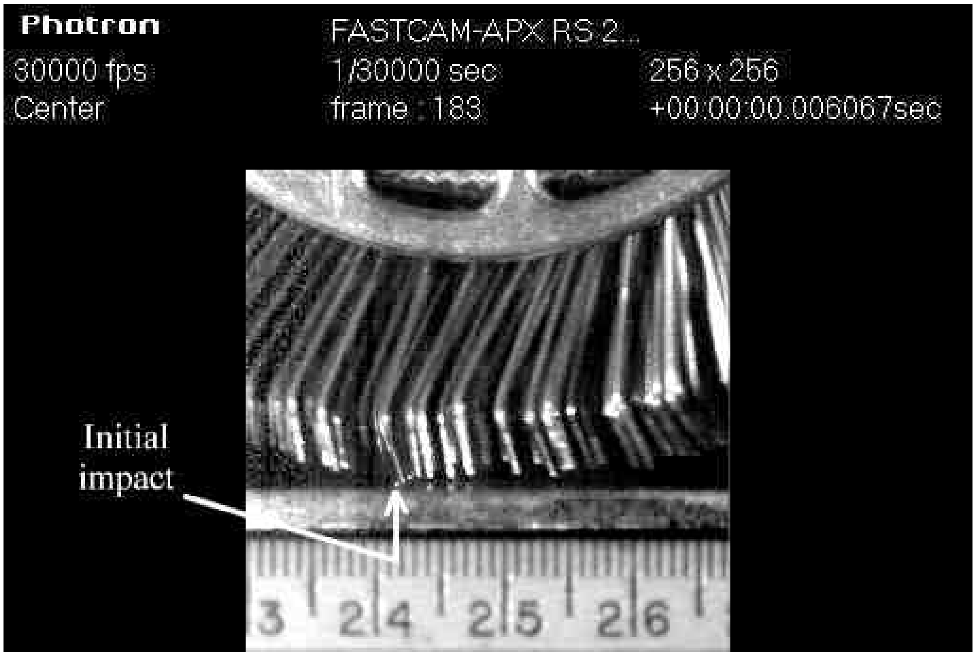


Figure 6 Single frame taken from high speed digital camera illustrating dynamic contact zone as bristle tips traverse the workpart surface (tool rotation is in counterclockwise direction)

Tool Implementation, Results, and Discussion

In this section, several matters of importance regarding the implementation and performance of bristle blasting tools will be examined. In particular, the following issues will be briefly addressed:

1. Corroded metallic components must be acquired, and their degree of corrosion must be objectively classified or "graded" in accordance with existing industry standards. This will establish a baseline for the severity of initial surface corrosion, thereby creating a benchmark for assessing the performance of the bristle blasting tool as well as a reference for comparing the performance of the tool to other commonly used methods of surface preparation. To this end, the initial condition of corroded metallic surfaces will be graded by employing standard practices that have been developed by the Steel Structures Painting Council (SSPC)[4,5].
2. The relationship between operating conditions and corrosion-removal performance of the bristle blasting tool will be briefly discussed. That is,

since the outcome of surface preparation processes are known to rely upon both tool performance and user-skills, several comments are warranted regarding mechanical aspects of the tools operation.

3. An objective method must be used to assess the corrosion removal capacity of the bristle blasting tool. That is, the post-treated surface must be qualitatively and quantitatively evaluated by using an objective means. To this end, standards that have been developed by the SSPC will again be used for appraising the outcome of surfaces that have been treated by the tool.
4. Finally, preliminary findings that pertain to the anticipated tool life should be made available to the end-user. This will enable engineers and cost analysts to evaluate any merit/benefit that can be derived by employing bristle blasting tools for surface preparation applications.

Selection of Corroded Test Specimens

Two different steel specimens that were acquired for assessing the corrosion removal performance of bristle blasting tools are shown in Figure 7, and consist of rolled, medium carbon steel having mill-scale along with some degree of surface corrosion (foreground), and medium carbon, square tubular steel having full-surface corrosion (background). Commensurate with SSPC guidelines[4,5], the

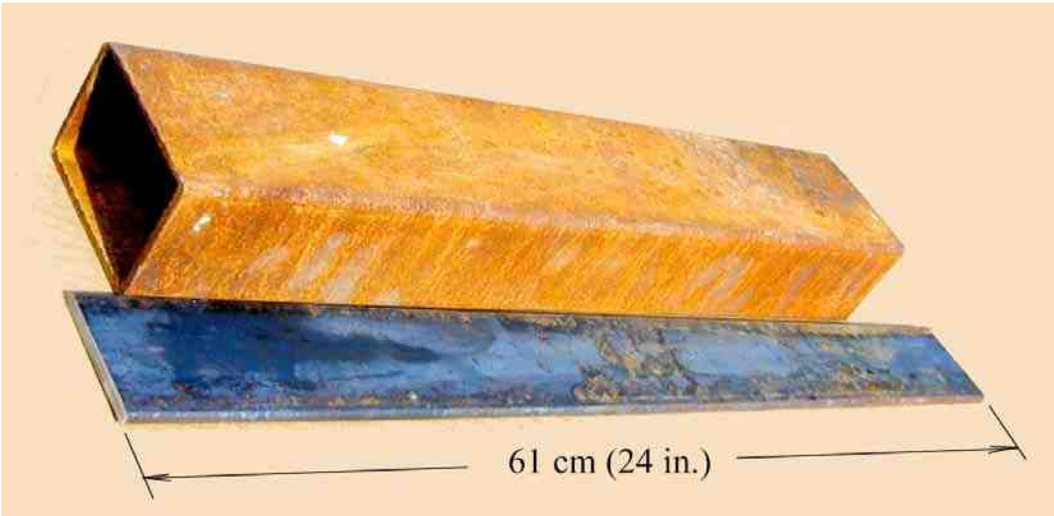


Figure7 Photograph of steel specimens that were acquired for assessing the corrosion removal performance of bristle blasting tools. Foreground: rolled, medium carbon steel having mill-scale along with some degree of surface corrosion. Background: medium carbon, square tubular steel having full-surface corrosion

initial rust conditions of these materials have been graded as follows:

Flat rolled steel
Condition B: Steel surface covered with both mill scale and rust.

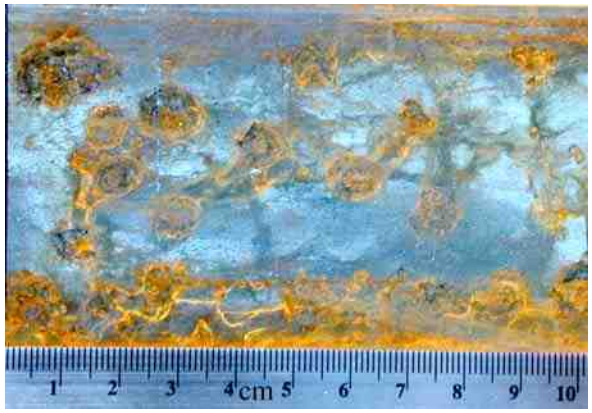


Figure 8 Photograph of flat rolled steel surface illustrating both mill scale and rust. The surface of this component has been assigned to SSPC Condition B: Steel surface covered with both mill scale and rust.

Square tubular steel
Condition C: Steel surface completely covered with rust; little or no pitting visible.

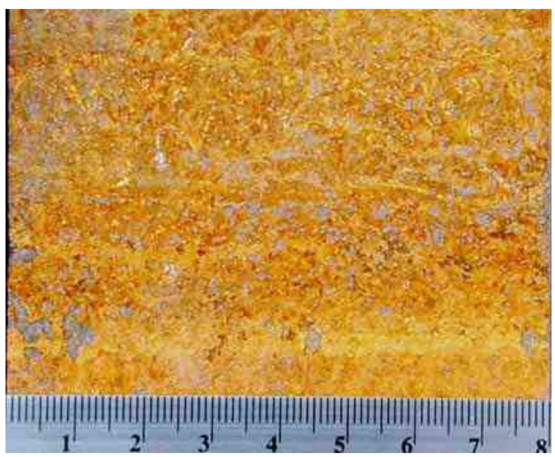


Figure 9 Photograph of square, tubular steel surface illustrating full coverage with rust. The surface of this component has been assigned to SSPC Condition C: Steel surface completely covered with rust; little or no pitting visible.

The photographs appearing in Figure 8 and Figure 9 were taken in natural light. Although glare has been removed from the photographs, no color change has been used to digitally enhance the pictures.

Implementation of Bristle Blasting Tool

Although guidelines for *optimal* use of the bristle blasting tool have yet to be established, comments and recommendations that pertain to implementation of the tool are briefly reviewed in this section. To this end, Figure 6 is reexamined, whereby a key performance feature of the tool can be observed. That is, primary impact of the bristle tips always occurs at the leading edge of the contact zone, and is generally followed by secondary/subsequent impact within the remaining portion of the contact region. Consequently, movement of the tool along the workpart surface from left-to-right (workpart is presumed to be fixed) will result in greatest coarseness (roughest surface texture). Conversely, movement of the tool from right-to-left will result in finer surface texture because secondary/subsequent impacts issued by bristle tips will diminish the coarse texture that was previously generated by primary bristle impact.

In general, performance of the bristle blasting tool follows similar principles that are associated with other well known impact-related processes. For example, the user-applied force and tool feed-rate can be varied by the operator so as to achieve surface features that are deemed necessary for a given application. Operator skill and training are, therefore, regarded as an essential part of surface conditioning processes. Further comments involving the surface treatment techniques that were used in the current work are discussed below.

Case 1: Bristle blasting of flat rolled steel - Condition B

Typical results obtained for the removal of mill scale and rust appearing in Figure 8 are shown below in Figure 10. The manual technique that was used for generating this surface texture is described as follows: First, the tool was applied to a test region of the workpart surface, and both the magnitude of the applied force and duration of contact were determined that produced a targeted surface appearance. Subsequently, the tool was applied to the workpart using lateral strokes (i.e., perpendicular to the feed direction) thereby generating a “row” of finished surface. Next the tool was incrementally advanced in the feed direction, (i.e., from left-to-right in Figure 10) and, once again, and a second lateral stroke was applied to the surface. The tool was repeatedly used in this manner, until all corrosion was removed from the steel surface.

Regarding the final appearance of the treated surface, one may observe that no trace evidence of corrosion remains. Furthermore, the treated surface does not exhibit elongated score marking (i.e., longitudinal scratches), which are characteristic of ordinary brushing processes. This is further evidence that the mechanism of corrosion removal is attributed to repeated impact and immediate retraction of bristle tips during tool operation. Equally important, the treated surface does not exhibit discoloration due to extreme temperatures that are often associated with ordinary brushing processes. Steel components were immediately handheld after bristle blasting, and no discernable temperature change was

Figure 10 Post-treated surface generated by bristle blasting of flat rolled steel (condition B, appearing in Figure 8)

detected. The photograph appearing in Figure 10 has also utilized natural light. Although glare has been removed from the photograph, no color change has been used to digitally enhance the picture.

Finer details of the surface structure are revealed in Figure 11 by using an optical microscope. Texture measurements of the treated surface

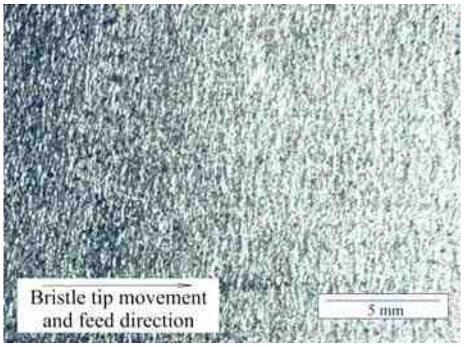


Figure 11 Higher magnification of post-treated surface generated by bristle blasting of flat rolled steel (condition B, appearing in Figure 8)

typically range from 50 µm-65 µm. An artificial light source was used when taking this photograph, which resulted in surface coloration. The photograph was then digitally enhanced in order to restore the original hue of the surface.

Case 2: Bristle blasting of square tubular steel - Condition C

Results that were obtained upon removing the rust shown in Figure 9 appear in Figure 12. The bristle blasting technique that was used for generating this surface is identical to that previously stated in *Case 1* and, therefore, will not be further discussed. One may observe that no trace of

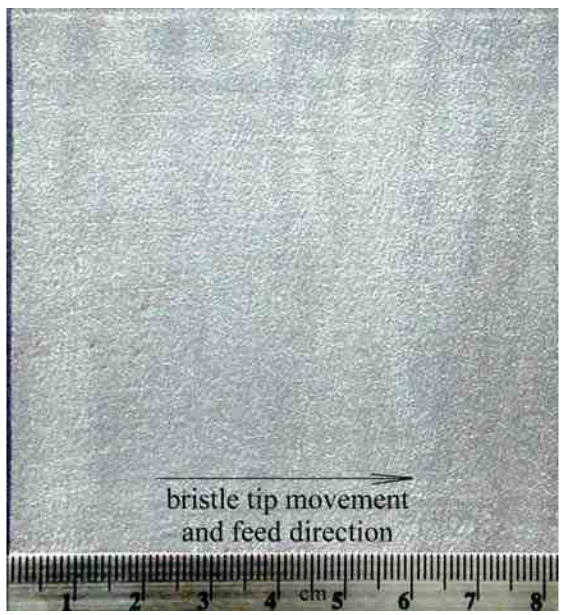


Figure 12 Post-treated surface generated by bristle blasting of square tubular steel (condition C, appearing in Figure 9)

residual corrosion can be seen on this surface, and that topographical features of the treated region are similar to those observed in *Case 1*. Also, as reported in *Case 1*, the surface is free of longitudinal score markings, and no discernable change in temperature could be detected immediately following the bristle blasting process.

Higher magnification of the treated region shown in Figure 12 appears in Figure 13, and reveals a detailed structure that is similar to that reported in *Case 1*. Surface texture measurements, again, typically ranged from 50 µm-65 µm.

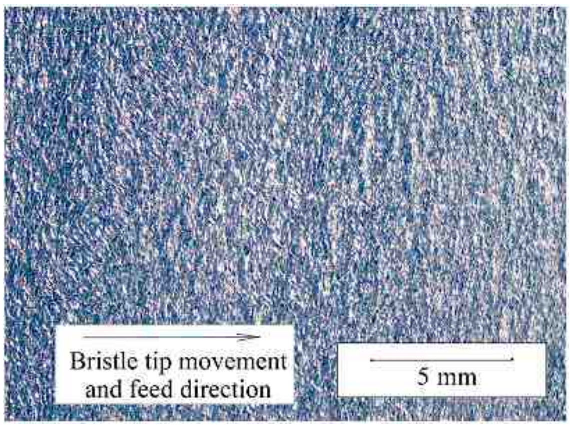


Figure 13 Higher magnification of post-treated surface generated by bristle blasting of square, tubular steel (condition C, appearing in Figure 9)

As previously discussed in *Case 1*, similar precautions were taken in the photographic digital enhancement of Figures 12 and 13.

Summary/Conclusion

Several observations can now be made regarding the degree of cleaning offered by the bristle blasting tool in relation to other standard methods that are commonly used in a production environment.

A direct comparison of bristle blasting with the photographs that have been published for various power tools and hand tools[5] indicates that the current approach clearly outperforms both conventional *wire brushes* and *sanding disks* (i.e., coated abrasives). Careful examination of Reference [5] suggests that the bristle blasting process is comparable to the cleanliness that is achieved by use of *rotary flap* and/or *needle gun* processes, i.e., “cleaning to bare metal”.

Likewise, a comparison of bristle blast cleaning performance can be made with published photographs that are indicative of dry abrasive blast cleaning[4] processes. In this case, thoroughness of the bristle blasting process apparently exceeds the cleanliness that is achieved by *brush-off blast cleaning* (SP 7), *industrial blast cleaning* (SP 14), *commercial blast cleaning* (SP 6), and *near-white blast cleaning* (SP 10). The result obtained by bristle blast cleaning, however, does appear to be comparable to *white metal blast cleaning* (SP 5).

The morphology of post-treated surfaces reported in this paper (i.e., Figures 10-13) indicates that the initially corroded surface profile is completely removed after the bristle blasting operation is performed. This is in contrast with photographs appearing in References 4 and 5, which indicate that certain features of the corroded surface are retained after the cleaning process. It is conjectured, therefore, that the bristle blasting tool that was used in the present work has an aggressive/erosive capability that outperforms existing methods of surface preparation. The implications of this finding and the potential impact that this outcome may have on the design and application of bristle blasting tools is currently under consideration by the author.

Finally, gradual erosion of the bristle tips during the re-sharpening process will inevitably lead to consumption of the hardened bristle shank and, consequently, retirement of the tool will be necessary. Recent studies have indicated that bristle blasting tools can clean/prepare at least 1 m^2 of corroded steel prior to retirement. This duration of tool life is encouraging, and suggests that the bristle blasting tool can be a viable option for many practical applications. Design modifications are now being examined that can significantly improve the longevity of tool life.

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