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Paper

ENHANCING THE PERFORMANCE OF PULSED WATERJETS FOR VARIOUS INDUSTRIAL APPLICATIONS

Wenzhuo Yan, Andrew Tieu, Baolin Ren, Bruce Daniels and Mohan Vijay
VLN Advanced Technologies Inc.
Ottawa, ON, Canada

ABSTRACT

Since introducing the concept of the forced pulsed waterjet (FPWJ) technique for a variety of applications, considerable progress has been made in improving its performance. For instance, recent work has demonstrated that increasing the pressure from 69 to 138 MPa (10 to 20 kpsi) increases the productivity by almost a factor of three. Based upon this observation, a new 138 MPa (20 kpsi) FPWJ generator (RFM) was developed and manufactured. Another advancement has been in increasing the width of removal of material from 51 mm (2 in) to well over 305 mm (12 in) per pass. The new device to achieve this goal is called TURN (***T***win ***U***ltrasonic ***R***otating ***N***ozzle). Preliminary tests, conducted on removing two layers of epoxy coating from a steel panel, have shown that the TURN is capable of removing ≈ 406 mm (16 in) wide swath of coating at a pressure of only 69 MPa (10 kpsi). The removal rate and specific energy were of the order of 22.3 m^2/hr (240 ft^2/hr) and 2.25 kW·hr/m^2 (0.28 hp·hr/ft^2) respectively. The surface finish was considered to be excellent.

1 INTRODUCTION

The most important requirement for advancing any waterjet technique for widespread industrial use, in addition to safety and acceptance, is productivity. As a unique waterjet technique, forced pulsed waterjet (FPWJ) has become increasingly attractive for many industrial applications, such as aerospace, automobile, marine, to name only a few. This is, in addition to its exceptional performance, due to its low capital and maintenance costs [**1**, **2** and **3**]. Until recently, FPWJ has been employed mainly in a single jet or, dual-orifice rotating mode of operations. Single FPWJ is a very powerful tool, which has been shown to be as the only green viable technique for the efficient removal of hard metallic coatings, such as HVOF, in the aerospace industry [**4**]. Dual-orifice rotating nozzles have also been found to be quite effective for the removal of hard epoxy coatings, hard deposits of chemicals on the inner wall of reactor vessels, and surface preparation of granite slabs in the mining industry [**5**]. Both the single and dual-orifice rotating nozzles are suitable for incorporation into automated systems, employed for instance, in aircraft engine maintenance, overhaul and repair centres [**6**]. Significant improvement in performance achieved by increasing the pressure from 69 MPa (10 kpsi) to 138 MPa (20 kpsi) would no doubt make FPWJ technique even more attractive for these applications. There are, however, many applications which require a waterjet system to remove a larger swath of material per pass [**7**]. For example, in the case of surface preparation of hull and deck of large ships or, cleaning of airport runways, it is important to remove 0.3 - 0.5 m (12 - 20 in) wide swaths per pass. The new device, called TURN (***T***win ***U***ltrasonic ***R***otating ***N***ozzle), was designed and manufactured for this purpose. In this paper, highlights of these developments are presented.

2 FPWJ TECHNIQUE

The authors have reported the method used for producing FPWJ in several publications [**6**]. Basically, the method consists of modulating a stream of water flowing through a regular nozzle (Fig. 1A). The modulation is achieved by placing an ultrasonic probe (called 'microtip') in the nozzle [**4**]. The microtip is energized by a transducer placed outside of the nozzle. An ultrasonic generator, rated to operate at a maximum power of 1.5-kW at 20-kHz, in turn powers the transducer. For a given set of flow conditions, when the input ultrasonic power is optimum, well-defined fully developed pulsed waterjet is produced (Fig. 1B). The shape of each pulse is like a mushroom, the size increasing with the standoff distance. The efficacy of FPWJ stems from:

1. The waterhammer pressure generated by the pulse at the point of impact on the workpiece is considerably higher than the stagnation pressure (≈ pump pressure) of a continuous waterjet. For instance, if the pump pressure is 69 MPa (10 kpsi), theoretically the magnitude of the waterhammer pressure is of the order of 552 MPa (80 kpsi).

2. The increase in diameter of each pulse with standoff distance (Fig. 1B).

3. High frequency (20-kHz) of impacts, which contributes to cyclic loading of the workpiece. Under the cyclic loading, the material yields quite readily, contributing to rapid removal process.

3 DESIGN CONSIDERATIONS AND MAJOR COMPONENTS

3.1 Model 2020 RFM (138 MPa, 20 kpsi)

3.1.1 Effect of Pressure on Performance of FPWJ

In all the earlier investigations reported in the literature [**1** and **2**], the 69 MPa (10 kpsi) FPWJ generator (RFM-2000) was used. However, a series of tests conducted on steel and aluminum panels received from ATK Thiokol (USA) showed that increasing the pressure beyond 69 MPa (10 kpsi) improves the performance significantly. Sample data on one of the samples are depicted in Fig. 2. The results indicate that not only do the removal rates increase almost by a factor of 2.8, the standoff distance at which peak performance occurs increases from about 25 to 100 mm (1.0 to 4 in). This latter observation is quite important for the cases where accessibility of the surface to be treated (e.g., corners) is of concern. The same trend was observed in processing other materials, as is evident from the data plotted in Fig. 3 for granite. The results clearly show that while the performance of FPWJ increases with pressure that of continuous waterjet (CWJ) deteriorates. The consideration to design and fabricate the 138 MPa (20 kpsi) RFM was based on these highly promising results.

3.1.2 Design Considerations

Figure 4A illustrates a general view of the cabinet 2020-RFM, which mainly includes a 1.5 kW ultrasonic generator, control components, pressure sensors and other accessories. The following sections give detailed descriptions of these components and the design considerations. Figure 4B shows the main outlets from the cabinet: (1) The trigger cable operates the dump gun, (2) high-pressure outlet and (3) the electrical pulse outlet, which transmits high frequency electrical pulses to the transducer which modulates the high-pressure water stream to produce FPWJ.

In order to ensure operator safety and other environmental considerations, several features were incorporated. It has been designed to function in harsh environments and to withstand high humidity, mist, debris and splashing water. All electronic and sensors are well protected in the heavy duty weather proof cabinet. The various controls and meters are located behind the weatherproof door. However, in order to deal quickly with emergency situations, the clearly visible ***emergency/main power switch*** is located outside of the door. Extensive testing of the 2020-RFM has been completed and Figure 5 depicts the promising results obtained with it. These results are discussed in **Section 4**.

3.2 TURN (Lawnmower Style Rotating Head)

A general view of the 'TURN' is shown in Fig. 6. Enclosed within the stainless steel drum are two independent single-orifice ultrasonic nozzle assemblies mounted on a rotating steel plate, which is driven by an electrical motor and pulley system. For manual operation, the drum, fitted with a rugged stainless steel handle, is mounted on four rubber castors. However, it is also possible to mount the drum on robotic arms by removing the handle and the castors. The following sections give a more detailed description of the design considerations.

It should be noted that as the transducer of each nozzle assembly requires its own ultrasonic generator, the 2020-RFM (Fig. 4) was slightly modified to house two ultrasonic generators. Since the purpose of 'TURN' is to process large surface areas, it is necessary to use large flow volumes at higher pressures. The RFM has been designed and manufactured to handle these requirements.

3.2.1 Rotating Nozzle Bodies

The major challenge in the design was providing electrical connection to the rotating transducers mounted on the nozzle bodies. This was accomplished by employing a specially designed slip-ring, fabricated by Honeybee Robotics (USA). The four-channel slip-ring, similar to rotating brushes used in electrical generators, was capable of handling high-voltage and fairly large current while rotating at a particular speed without generating sparks. The rotating plate is driven by a DC electrical motor and pulley system. The DC motor is in turn powered by an onboard power supply. The rotational speed and direction of the plate are thus fully controllable by the operator. This motor driving mechanism has proven to be quite useful in providing rotating speed and direction data for performance evaluation.

3.2.2 Standoff distance control

A mechanical device is incorporated into the drum to vary the standoff distance manually. The range from 13 to 127 mm (0.5 to 5.0 in) is considered to be satisfactory for many industrial applications.

3.2.3 Angle of Orientation and Width of Swath

The width of the swath per pass of the traverse of the 'TURN' over a target depends on the angle of orientation of the two rotating nozzle bodies with respect to the axis of rotation. Although the angle of orientation of the nozzles (jets) can be varied from 0º (vertical) to about 20º, an angle of 15º proved to be optimum from the standpoint of maximum removal rate. Increasing the angle from 0^o to 20^o increases the width of swath from 16 in 406 mm (16 in) to about 483 mm (19 in), however, at a slight loss of removal rate.

3.2.4 Mobility

For manual operations, 'TURN' can be easily moved around over the surface to be processed with the heavy duty handle. The rubber wheels make it possible to move it around over rough surfaces {≈ 25 mm (1 in.) in irregularities}.

3.2.5 Safety

Operator safety is always the most important consideration in the design of any waterjet system.

In the case of RFM and 'TURN', since high-voltage pulses are transmitted from the ultrasonic generators to the transducer-nozzle assemblies, ensuring operator safety becomes even more demanding. Thus, every precaution was taken to prevent the accidental exposure to electric shocks. For instance, as shown in Fig. 4B, the coaxial cable, which carries the electrical signals, is protected by enclosing it in an air filled rubber hose. The air in this hose cools the ultrasonic transducers. The air pressure is constantly monitored by a sensor located inside the cabinet. In the event of rupture of the hose, the pressure drops immediately below a certain preset value, turning off the ultrasonic power generator. As a result the operator is fully protected from getting an electrical shock from the damaged cable. Likewise, water pressure sensors installed which ensure safe operation of both machines.

4 DISCUSSION OF RESULTS OBTAINED WITH THE RFM AND TURN

The performance indicators of both the 2020-RFM and the 'TURN' are: (1) surface profile, (2) removal rates and (3) specific energy. Coatings removal tests were conducted to compare the performance of the 'TURN' with the corresponding single-orifice and the dual-orifice rotating nozzles. Panels coated with non-skid marine coating, those obtained from ATK Thiokol, USA (the properties of coatings are not known), and dual-layer epoxy paints were used. Results acquired to date have shown great promise of the 'TURN' for treating large surface areas.

Figures 5, 7 and 8: These figures illustrate typical appearance of the substrates after removing the coatings. The swaths {≈ 25 mm (1 in wide) depicted in Fig. 5 were obtained by consecutive passes with a single-orifice non-rotating nozzle at the operating conditions as indicated. Figure 7 shows the wide swath {≈ 0.41 m (16 in)} of non-skid coat removed with the 'TURN' in a single pass at 69 MPa (10 kpsi). Figure 8 shows the surface finish of ATK panel, also obtained at 69 MPa (the dual-orifice nozzle is shown just for comparison). The area removal rate and the specific energy for this panel were 7.4 m^2/hr (80 ft^2/hr) and 4.6 kW-hr/m^2 (0.58 hp-hr/ft^2) respectively. In all cases surface finish of the panels is considered to be excellent (bare metal with no damage to the substrate).

Figure 9: The area removal rates (ARR), specific energy (SE) results obtained with the single-orifice nozzle, dual-orifice rotating nozzle (SA) and the 'TURN' are plotted in this figure on the same panel shown in Fig. 5. These limited comparative tests were conducted at 69 and 103 MPa (10 & 15 kpsi) using three different orifice diameters {0.762 mm (0.03 in), 0.889 mm (0.035 in) and 1.016 mm (0.040 in)}. The main observations from this plot are:

- In the case single-orifice non-rotating nozzle and the 'TURN', for a given pressure, area removal rates increase with the increase in orifice diameter. While the increase is only modest for the single-orifice nozzle, it is quite significant for the 'TURN'. For example, at 103 MPa (15 kpsi), the area removal rate increases by a factor of 3.5 when the nozzle diameter is increased from 0.762 mm (0.030 in.) to 1.016 mm (0.040 in.). This indicates further improvements can be achieved by increasing the diameter of each orifice in the 'TURN'.

- Similar trends are observed with respect to increase in pressure for a given orifice diameter. For instance, for the 1.016 mm (0.04 in) orifices in the 'TURN', when the pressure is increased from 69 MPa (10 kpsi) to 103 MPa (15 kpsi), the area removal rate increases almost by factor of two. These observations are in keeping with the data plotted in Fig. 2 and Fig. 3.

- With respect to dual-orifice rotating nozzle (SA), ubiquitously used in all the earlier work [**1** to **8**], conducted only using 1.016 (0.04 in) orifices, the area removal rate at 69 MPa (10 kpsi) is poor, compared to both the single-orifice nozzle and the 'TURN'. While its performance improved significantly when the pressure was increased to 103 MPa (15 kpsi), it is still quite poor compared to the performance of 'TURN'. The poor performance of the dual-orifice rotating nozzle at 69 MPa (10 kpsi) is attributed to the losses due to the complex internal flow paths.

- The specific energy curves (dotted lines) hold the same trends relative to the corresponding area removal rates.

These observations clearly indicate the benefits of using the 'TURN' for processing large surface areas, such as ship decks, airport runways, and highways.

5 CONCLUSIONS

Previous extensive work conducted showed that it is possible to enhance the performance of FPWJ by increasing: (1) the pressure up to 138 MPa (20 kpsi) and (2) the width of swaths of material removal. Based on this finding a new FPWJ generator (2020 RFM) and a device called 'TURN (***T***win ***U***ltrasonic ***R***otating ***N***ozzle) were fabricated and tested in the laboratory. The conclusions from the test results are:

1. It is possible to enhance the area removal rates significantly by increasing the pressure. In the case of 'TURN', the area removal rate increased from 11 to 21 m^2/hr (118 to 226 ft^2/hr) when the pressure was increased from 69 to 103 MPa (10 to 15 kpsi). The trend of the data indicates the performance would increase with further increase in pressure.

2. The data also show that it is possible to enhance the performance by increasing the orifice diameter. At a pressure of 103 MPa (15 kpsi), the area removal rate of the marine coating achieved with the 'TURN' increased from about 6.5 to 21 m^2/hr (70 to 226 ft^2/hr) with the increase in orifice diameter from 0.76 to 1.016 mm (0.03 to 0.04 in). The trend of the data indicates the performance would increase with further increase in orifice diameter.

3. In all cases the surface finish (profile) is considered to be excellent.

4. Further work is in progress to validate the trends stated for a variety of other applications.

6 ACKNOWLEDGMENTS

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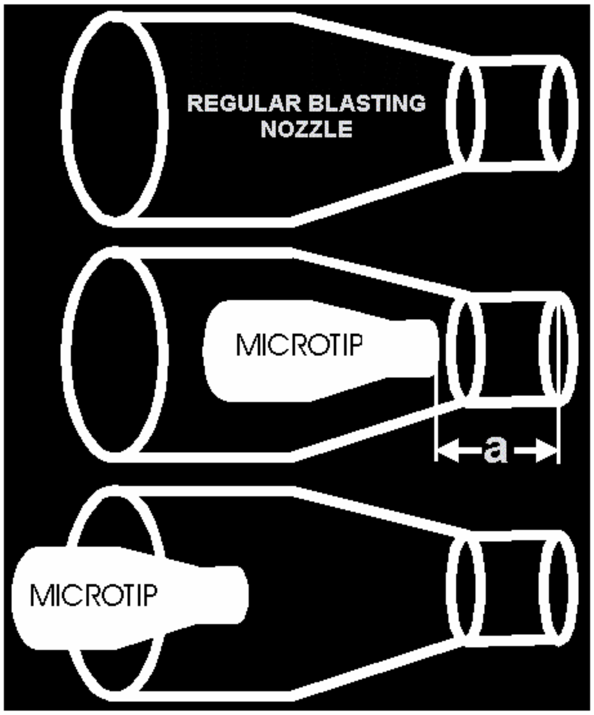

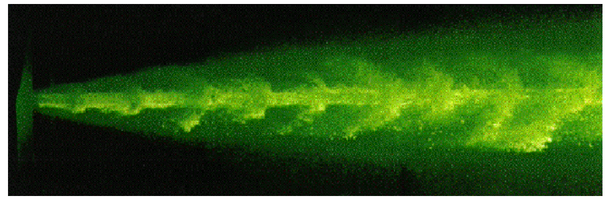

Fig. 1B. Photograph of the well-defined and fully developed FPWJ taken with a Nd-Yag Laser [**6**].

Fig. 1A. Modulation method used for producing the FPWJ.

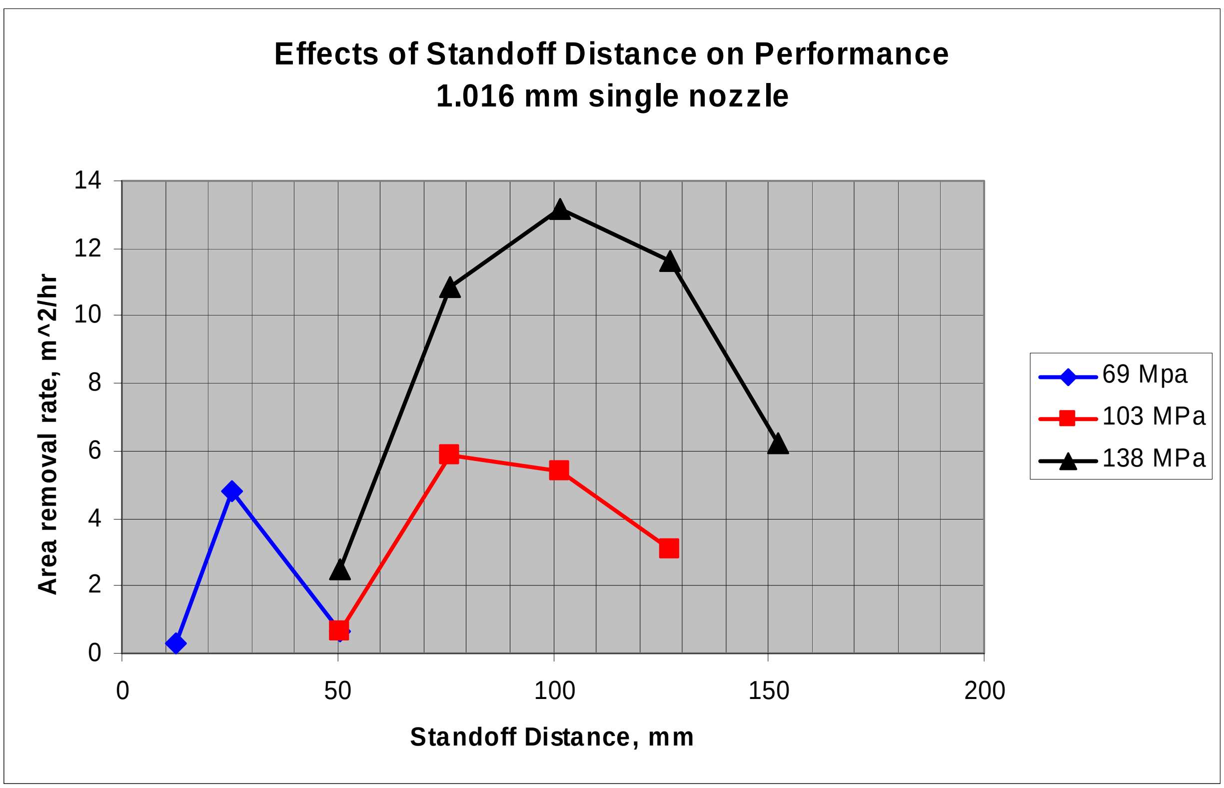

Fig. 2. Plot of removal rate against standoff distance showing the effect of pressure.

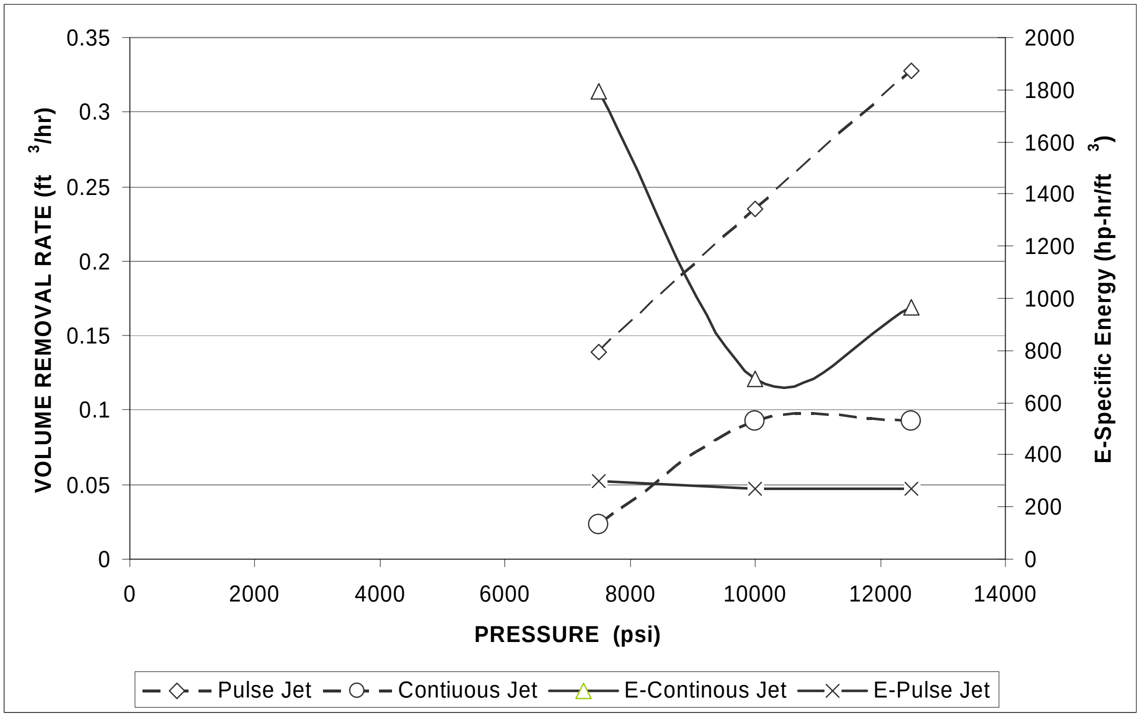

Fig. 3. Comparison of the performance of FPWJ with corresponding continuous waterjet (CWJ) for cutting granite. The data show the effect of pressure on volume removal rate and specific energy.

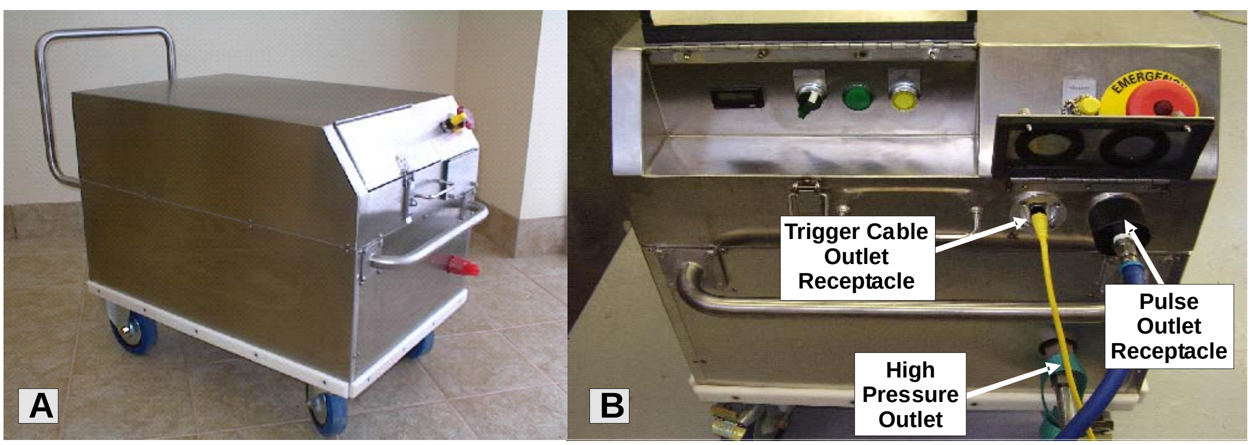

Fig. 4. A General view of the model 2020 RFM, depicting some of the important components.

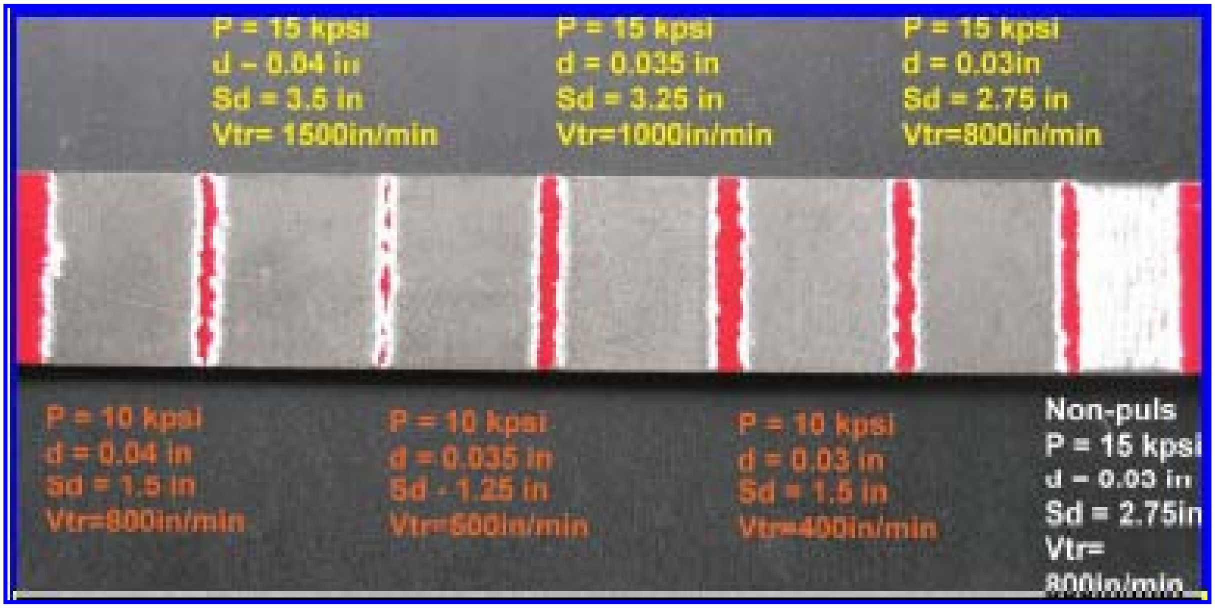

Fig. 5. Photograph showing the removal of two layers of epoxy coating from a marine steel panel with a single-orifice non-rotating FPWJ at operating conditions as indicated.

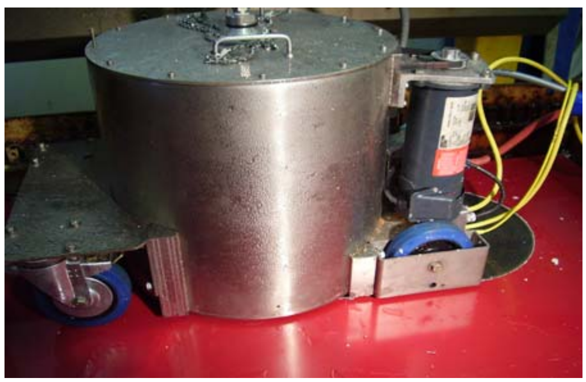

Fig. 6. A general view of the TURN.

Fig. 7. Photograph showing the TURN set up for removing the non-skid coating from a steel panel at 10 kpsi (69

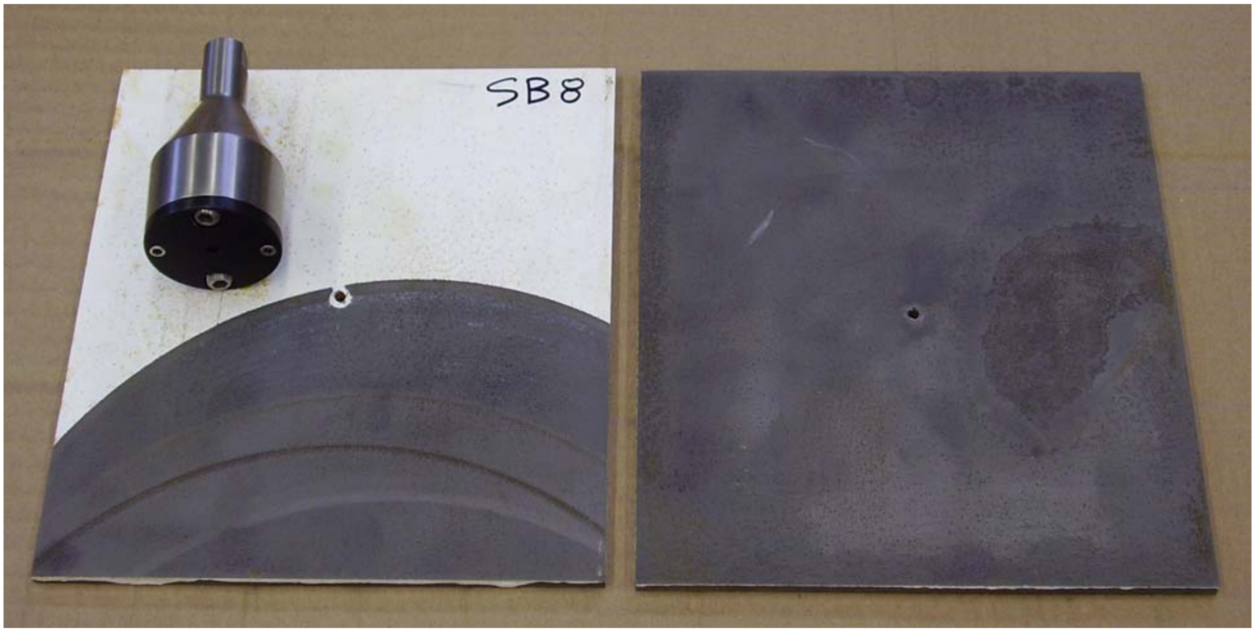

Fig. 8. Typical appearance of the substrate from which two layers of epoxy coatings were removed with the TURN (sample received from ATK Thiokol, USA). Dual-orifice rotating nozzle is shown for comparison.

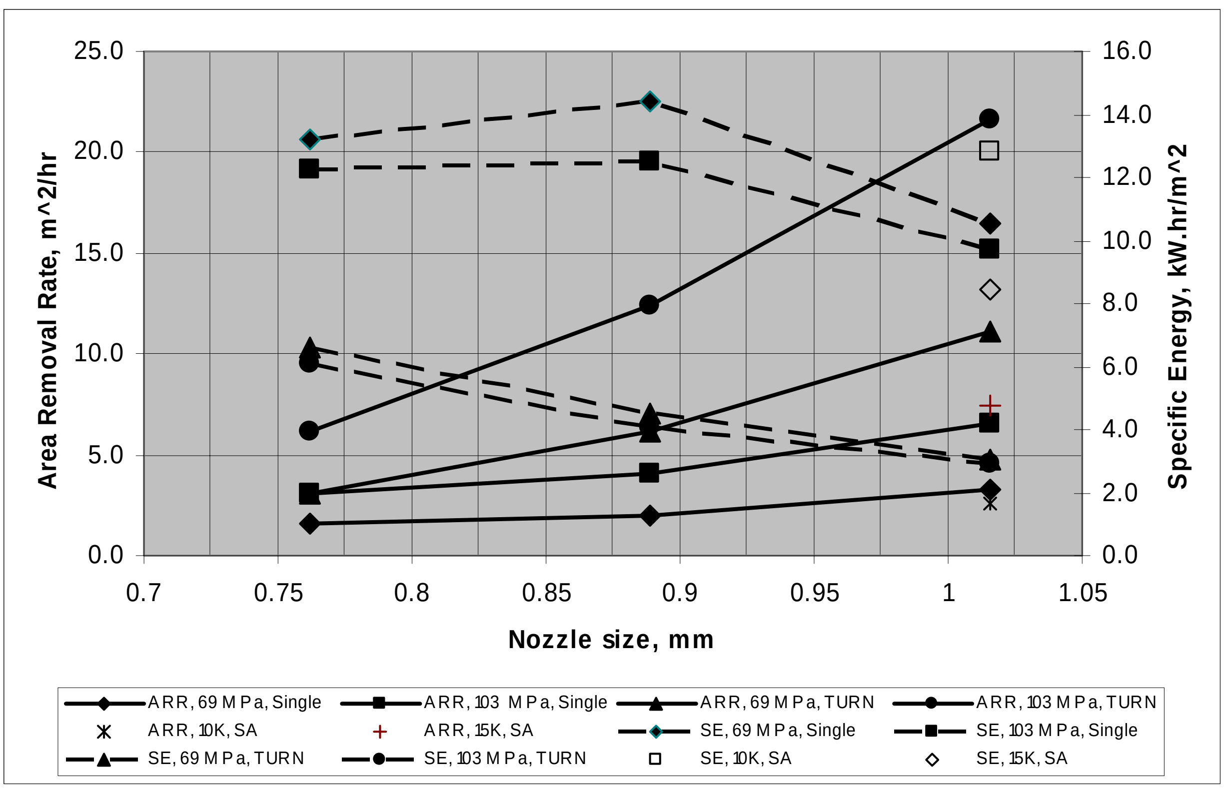

Fig. 9. Plot of removal rates and specific energies obtained with single-orifice, dual-orifice rotating (indicated by 'SA') and the TURN at the operating conditions as indicated.