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Paper

HEAT EXCHANGER TUBE MATERIAL RESPONSE TO HIGH PRESSURE WATERJET IMPACT AND THE FACTORS AFFECTING THE RISK OF DAMAGE DURING THE CLEANING PROCESS

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ABSTRACT

The utilization of waterjets for the cleaning of heat exchanger tubes is widely accepted in industries around the world. The fouling or scales that form during use typically determine the specified operating pressure of the waterjet cleaning system, often in the range of 69 to 276 MPa (10,000 to 40,000 psi). While carbon steel and stainless steel tube materials are reasonably resistant to properly applied waterjet cleaning techniques, other softer metallic materials consisting of brass, nickel, and copper alloys are commonly used in tube and shell heat exchanger construction and their potential for damage by high pressure jet erosion is expected to be greater. While operating pressure is one of the primary factors in the risk of damage to all tube materials, other parameters of the cleaning system play a role, such as the movement of the jets by rotation of the lance or nozzle head, the rate or pause of translation of the nozzle head through the tube, and the jet angle of impingement on the inside of the tube wall. The purpose of this research was to test and present the effect of increasing jet pressure combined with other parameters that determine the probability of the erosion that may occur on common metallic tube materials such as carbon and stainless steel, brass, copper, titanium, and nickel alloys.

1. INTRODUCTION

The impact of a plain (not abrasive) waterjet on a metallic surface can remove material through the process of cavitation erosion. The amount or depth of material removal is primarily dependent on the material type, the pressure of the jet, if the jet is fixed or in a rotating nozzle head, and the time that the jet is left in one place without being continuously translated, whether rotating or not. Standoff distance of the jet to the tube wall, jet angle of impact and orifice size also affect the rate of material removal by lesser amounts.

The selection of operating pressure for the cleaning of heat exchanger tubes is generally based on operator experience in removing specific types of deposits from the tubes and does not always take into consideration the tube material, nozzle type, or the methods of the workers performing the cleaning. As an example, it is a common practice to place the nozzle in a stationary position inside a clean tube while setting the operating pressure. A worker might also leave a nozzle in place against a hard deposit or plug in the tube, waiting for the jets to clear the material instead of continuously moving the nozzle. The potential amount of damage in either case is also dependent on whether the nozzle is rotating or stationary, as well as the time that the nozzle is left in one place. Alternatively, a trained and aware worker or an automated system programmed to not allow a nozzle to be left in one place while at pressure might allow acceptance of higher operating pressures for cleaning if needed for faster or more effective cleaning.

This paper presents the potential of cavitation erosion with the variables of pressure, time of exposure, static jets and rotating jet heads on different materials commonly used in heat exchanger construction, to allow owners of equipment and waterblast cleaning services to determine risk of damage, and to specify cleaning pressures combined with methods or controls of application to optimize the cleaning process while minimizing the potential risk.

2. TEST PROCEDURES

The material samples used in the tests consisted of tube and flat plate, depending on material availability. The plate samples were the primary means as they were simpler to set up and measure after tests were performed. Table 1 lists the materials and designations.

The first series of non-rotary tests performed on each material type consisted of a typical nozzle head with radial jets installed on a fixed piece of high pressure tubing with one jet aimed directly at the surface, set at a standoff distance of 4.8 mm from the material surface. Table 2 describes the nozzle heads used in the tests. The system was brought to the desired test pressure and the head traversed onto the material and paused for each separate time of exposure. Figure 1 illustrates this nozzle head and test arrangement.

The second series of tests was performed with the same nozzle head type installed on a self-rotating tube nozzle assembly, with a standoff distance of 4.8 mm from the material surface except when determining effect of varied standoff distance. The system was again brought to the desired test pressure and the spinning head traversed onto the material and paused for each separate time of exposure. Figure 2 illustrates this tool and test arrangement. The effects of larger and smaller orifice sizes were also compared with the rotary test.

The third series of tests consisted of traversing the rotating nozzle head back and forth across an area of the sample material with up to 100 passes at a rate of 50 mm/s to evaluate the effect of repeated cleaning cycles with a continuously moving and rotating nozzle.

3. TEST RESULTS

3.1 Non-Rotating Jet Effect

The results of the non-rotary jet testing for all the materials are shown in Figure 3, where a test pressure of 103 MPa (15,000 psi) was applied through Nozzle Head "A" with an orifice size of .9 mm (.036 in) impacting the material, for time periods of 10, 30, and 60 seconds. The soft copper and copper alloys showed the greatest effect, while the Monel, Titanium and Stainless Steel show the least. This chart illustrates the relative difference of effect at the same pressure between all the material types as a reference point. For all materials, the non-rotating jet did not remove any material when traversed between the timed test points.

From these results, the materials could be divided into "Soft" and "Hard" as to their resistance to erosion by jet impact. Figure 4 plots the results of the non-rotary jet on Copper, Copper-Nickel 90/10, and Brass 260 at the lower pressures of 55 MPa (8,000 psi) and 69 MPa (10,000 psi). If no controls on operational methods were in place, the pressure might need to be limited still further for the Copper and Copper-Nickel alloys to avoid damage to the tube wall.

The relatively "Hard" materials, with greater resistance to non-rotary jet erosion were the Monel, 1018 CS, 304 SS and Titanium, with the 304 SS being most resistant, followed by the Titanium. Figure 5 shows the results in these materials with the non-rotary jet impact at pressures of 69 MPa (10,000 psi), 103 MPa (15,000 psi) and 138 MPa (20,000 psi). Without controls on operation, maximum pressures for these materials might need to be limited as well.

3.2 Rotating Jet Effect

Rotating the nozzle head results in continuous motion of the jet across the surface, which by itself reduces the amount of potential damage to the surface, although if left rotating in the same place for periods of time, erosion can still occur. The application of the rotating nozzle head allows potentially higher operating pressures for any material. Figure 6 illustrates the difference between non-rotary and rotary at 103 MPa (15,000 psi) for the Copper-Nickel 90/10 and 1018 Carbon Steel; the depth of material removed can differ by a factor of 10 for the same pressure and time of exposure.

From Figure 7, a rotary head pressure of 69 MPa (10,000 psi) could be acceptable for the Copper-Nickel 90/10 but still at risk for the Copper 110 material without operational controls. Figure 8 shows the resulting effect when the pressure increased to 103 MPa (15,000 psi) in these same materials as well as 1018 Carbon Steel; it would be necessary to prevent the nozzle head from stopping translation to avoid tube wall damage at this pressure in these materials.

Figures 9 and 10 show the results of rotary head testing at 103 MPa (15,000 psi) and 138 MPa (20,000 psi) on Monel 400, 304 Stainless Steel, 1018 Carbon Steel and Titanium. The 304 SS was the most resistant, followed by Titanium and Monel, which essentially fall in between the 304 SS and the 1018 Carbon Steel in their resistance to cavitation erosion. Figure 11 shows the result in the same materials at 228 MPa (33,000 psi) with reduced times of exposure to demonstrate the importance of not allowing the nozzle head translation to be paused during the cleaning process with higher operating pressures.

3.3 Standoff Distance, Jet Power and Jet Angle Effects

The effect of standoff distance was tested with the rotating nozzle head arrangement within the range that might be found in tube cleaning, and as has been previously shown with cavitation, there is an optimum distance for the greatest effect, and no effect if the jet orifice is against the surface. This response is related to how the jet breaks up into droplets as it travels through the air or water before contacting the surface. Figure 12 shows the results of these tests conducted on 304 Stainless Steel at 138 MPa (20,000 psi) and Copper-Nickel 90/10 at 69 MPa (10,000 psi) with an exposure time of 30 seconds at each point.

The effect of increasing the jet power through increased flow rate was also tested with the rotating nozzle head arrangement, in 1018 Carbon Steel at 138 MPa (20,000 psi), comparing the Nozzle Head “A” with a .91 mm (.036”) orifice size to Nozzle Head “D” with a .66 mm (.026”) orifice size. At short exposure time periods there was minimal difference, while at the maximum 60 second exposure the higher flow rate head did remove more material. These results are shown in Figure 13.

The effect of jet angle of impingement on the surface of the material was tested to determine if there would be a reduction in damage with less direct impact. This did prove to be true at a 15 degree angle of impact, but at a 30 degree angle to the surface, the damage had increased to nearly half that of the 90 degree impact result, as shown in Figure 14, conducted on the Copper 110 plate at 138 MPa (20,000 psi) for 60 seconds.

3.4 Rotating and Traversing Jet Effects

This series of tests was conducted by traversing the rotating nozzle arrangement back and forth for multiple passes across the same surface area, at a rate of 50 mm/s. None of the tests produced a measurable erosion rate, although the surface generally ended up with a frosted appearance. This highlights the importance of maintaining continuous motion to minimize or avoid damage to the tube wall surface in any material. Figure 15 shows Copper 110 after test at 103 MPa (15,000 psi) and 100 passes across the surface. Figure 16 shows 1018 Carbon Steel after test at 228 MPa (33,000 psi) and 50 passes; Figures 17 and 18 show Monel and Titanium after 50 passes each at 228 MPa (33,000 psi).

4. CONCLUSIONS

This testing was performed to aid in the specification of heat exchanger tube cleaning processes, from operating pressure to types of nozzle heads and personnel training for operating procedures. There exists a pressure threshold below which would result in minimal damage to the tube wall over an extended period of time of jet exposure; however, this pressure threshold may be below that needed to effectively remove a deposit at a reasonable rate. Utilizing training or automated controls to ensure that the nozzle head maintains rotation and feed rate while operating at cleaning pressure is the most effective means of avoiding damage to the tube wall.

Regarding the material types and their resistance to jet erosion, it was found that the Copper and Copper Nickel alloys would be most susceptible to damage with higher pressures, and operating pressures should be limited in the range of 48 to 69 MPa (8,000 to 10,000 psi) at maximum. The Monel 400, Titanium Type 2 and 304 Stainless Steel exhibited the greatest resistance to damage by jet erosion, and operating pressures in the range of 103 to 138 MPa (15,000 to 20,000 psi) with moderate operational control would be acceptable. Higher cleaning pressures in the range of 200 to 280 MPa (30,000 to 40,000 psi) should always have operational controls in place to limit or avoid jet damage.

Material	UNS	Form	Other Common Names
Copper-Nickel 90/10	C70600	Sheet	Cupro-Nickel
110 Copper	C11000	Sheet	CDA 110
101 Copper	C10100	Tube	C101
260 Brass	C26000	Tube	Cartridge Brass
400 Nickel	N04400	Sheet	Monel 400
304 Stainless Steel	S30400	Plate	304 Stainless Steel
1018 CDF Carbon Steel	G10180	Plate	1018 Carbon Steel
Titanium Grade 2	R50400	Sheet	Titanium Type 2

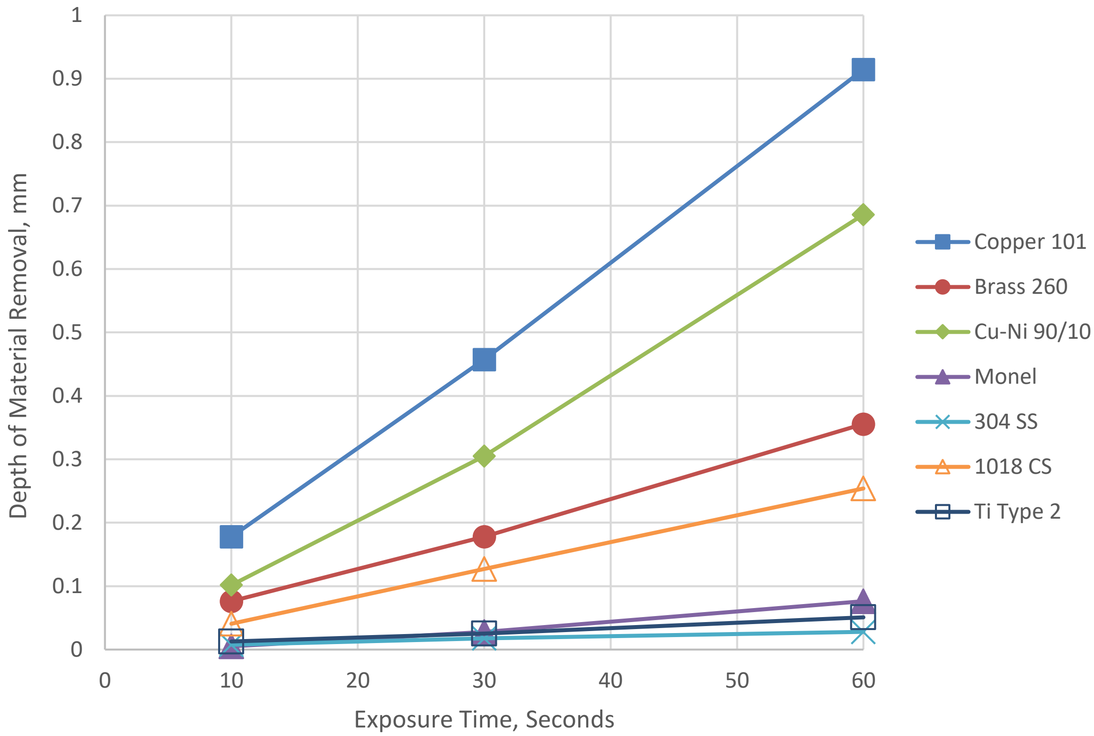
Materials and Designations Used in Testing
Table 1.

Head Name	Orifice Type	Pattern 1	Orifice Size	Pattern 2	Orifice Size
"A"	Drilled	2 X 90°	.91 mm (.036")	2 X 105°	.81 mm (.032")
"D"	Drilled	2 X 90°	.66 mm (.026")	2 X 105°	.66 mm (.026")
"UHP"	Sapphire	2 X 85°	.25 mm (.010")	2 X 110°	.36 mm (.014")

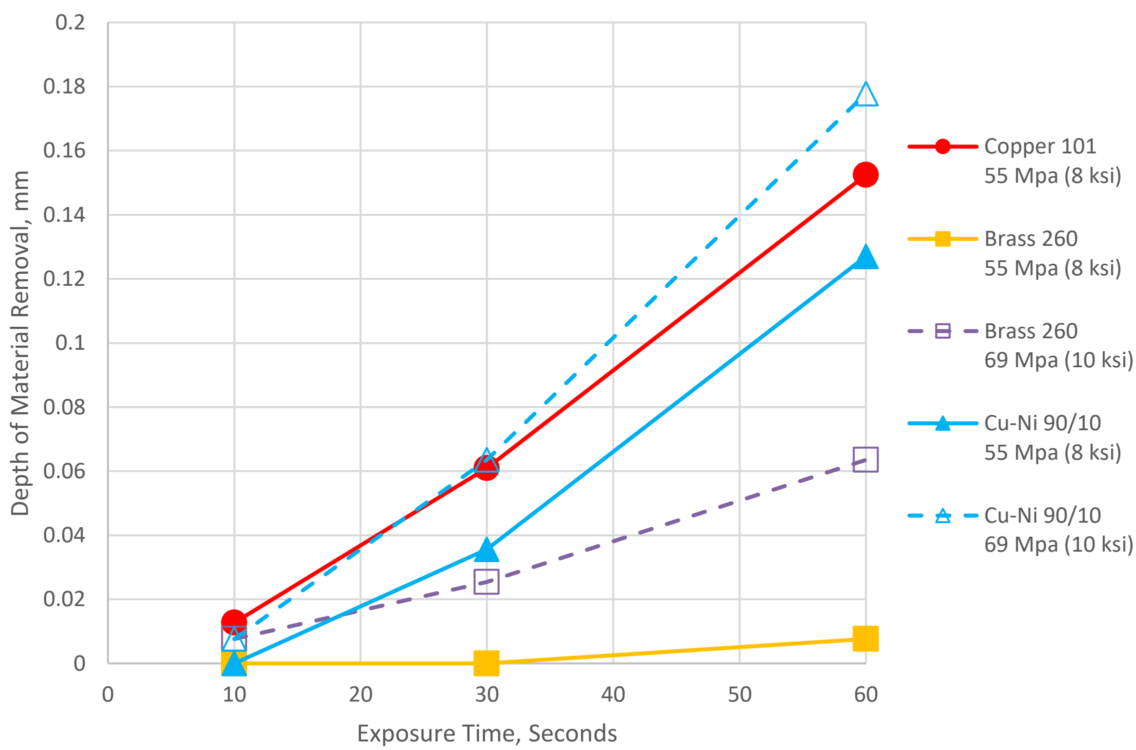
Nozzle Heads Used in Testing
Table 2.

Non-Rotary Head Test Arrangement Shown with Copper Nickel 90/10 Sheet
Figure 1.

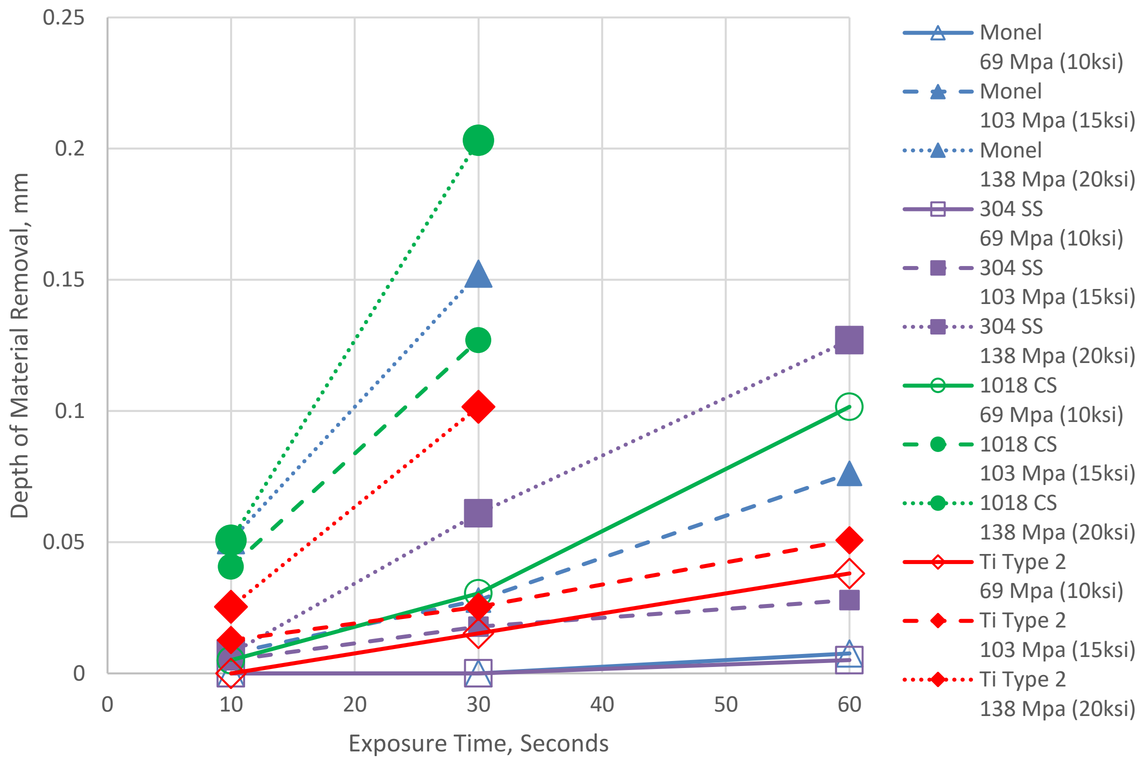
Self-Rotary Tube Nozzle Assembly Test Arrangement and Results in Copper Nickel
Figure 2.



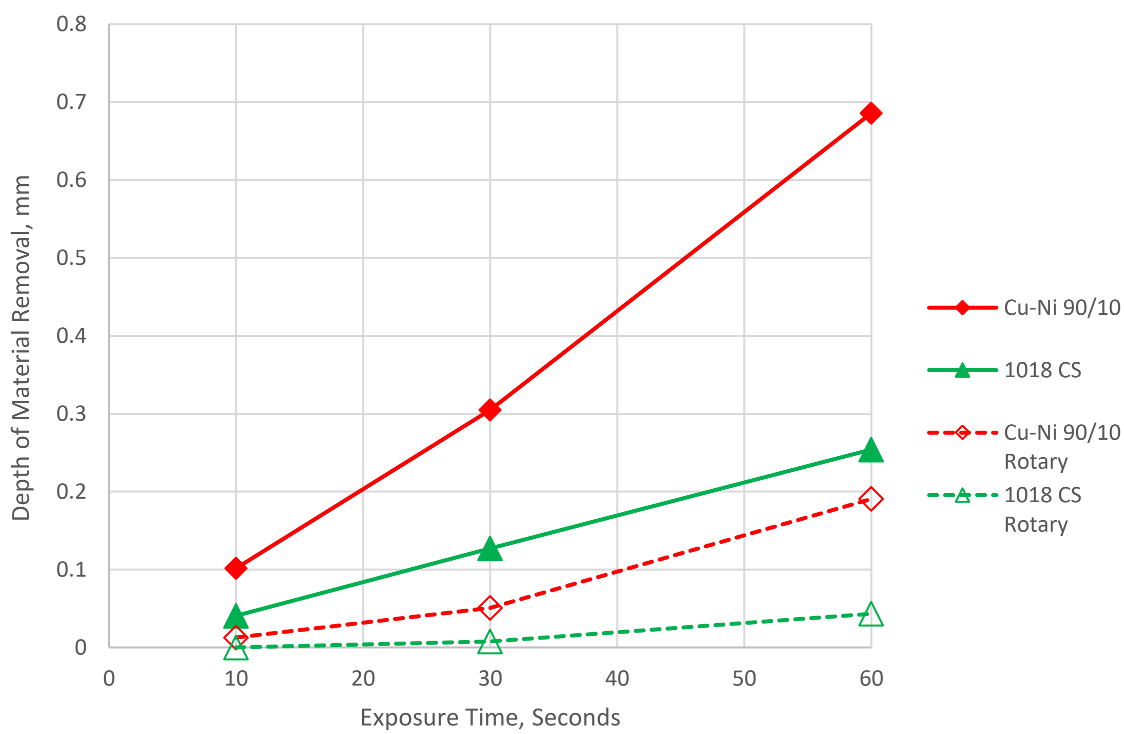
Relative Effect of Non-Rotary Jet Applied at 103 MPa (15,000 psi)
Figure 3.



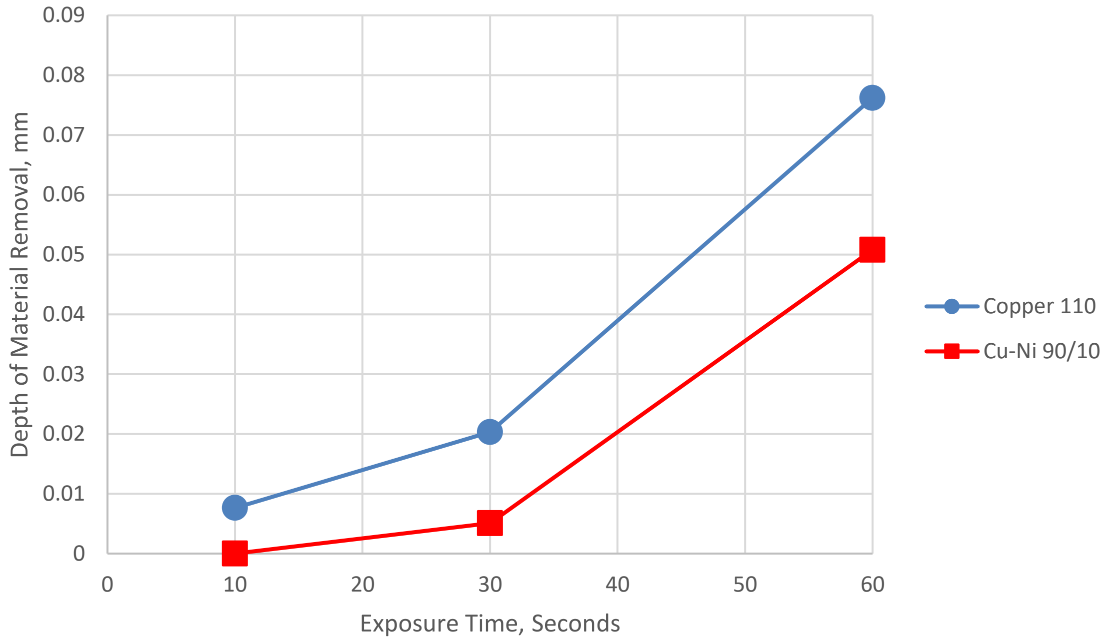
Effect of Non-Rotary Jet at Lower Pressures for "Soft" Materials
Figure 4.



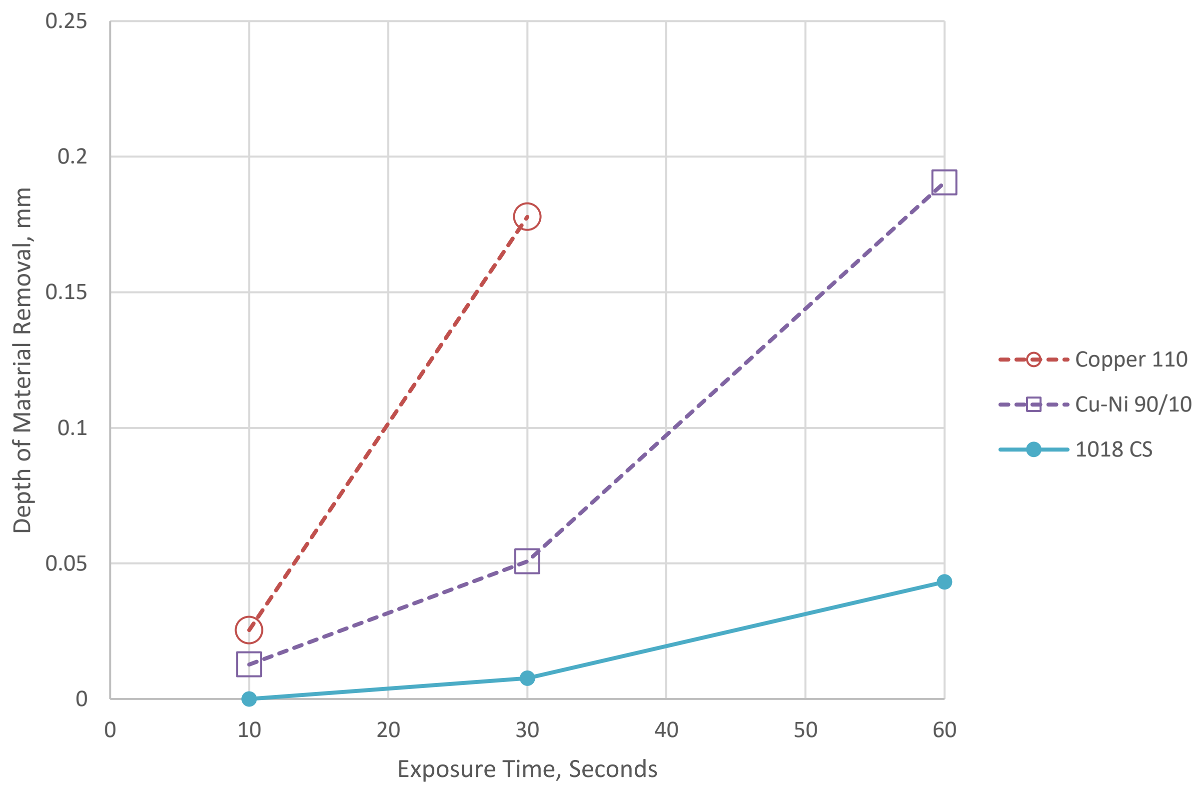
Effect of Non-Rotary Jet at Pressures up to 138 MPa (20,000 psi) for "Hard" Materials
Figure 5.



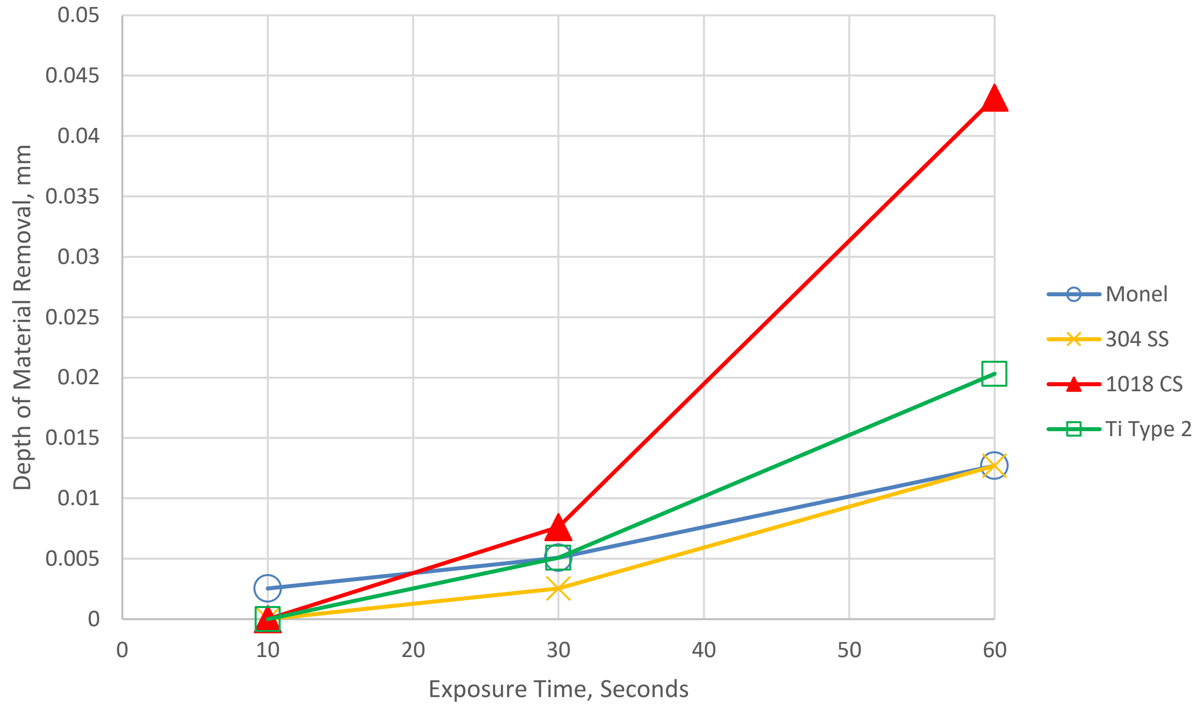
Comparison of Rotating Head to Non-Rotary in Two Materials at 103 MPa (15,000 psi)
Figure 6.



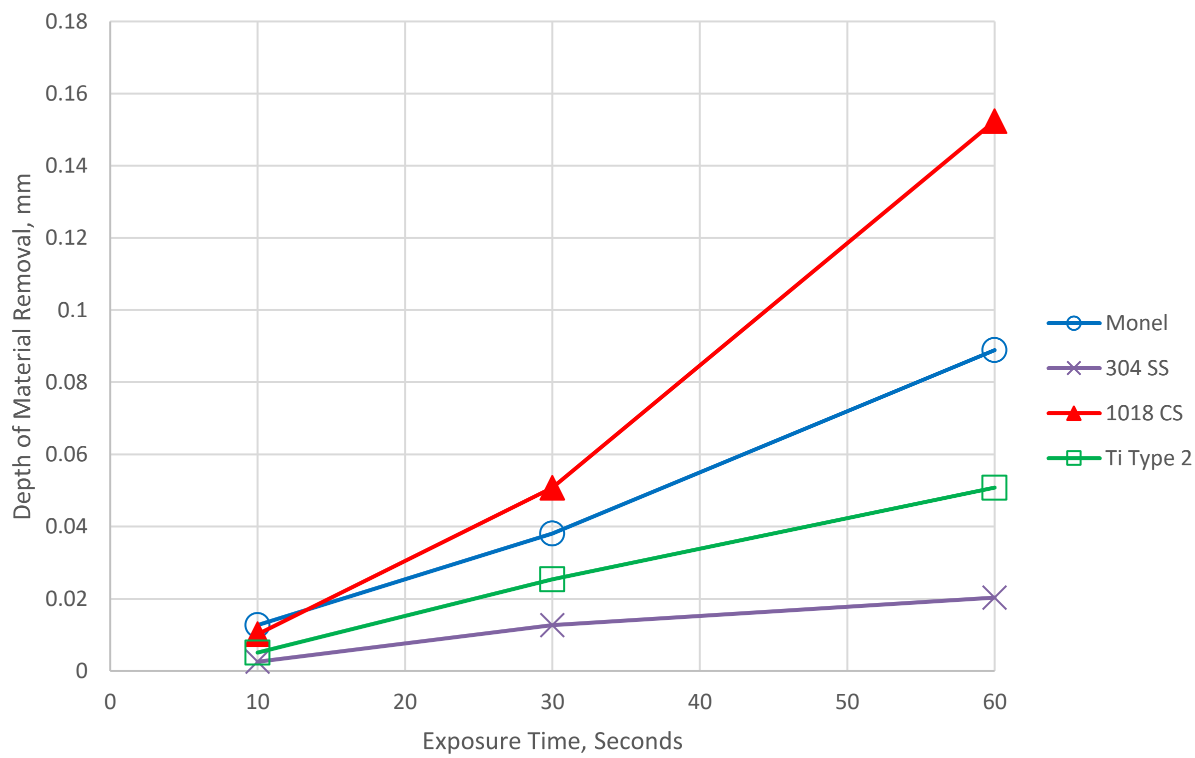
Copper 110 and Copper-Nickel 90/10 with Rotating Head at 69 MPa (10,000 psi)
Figure 7.



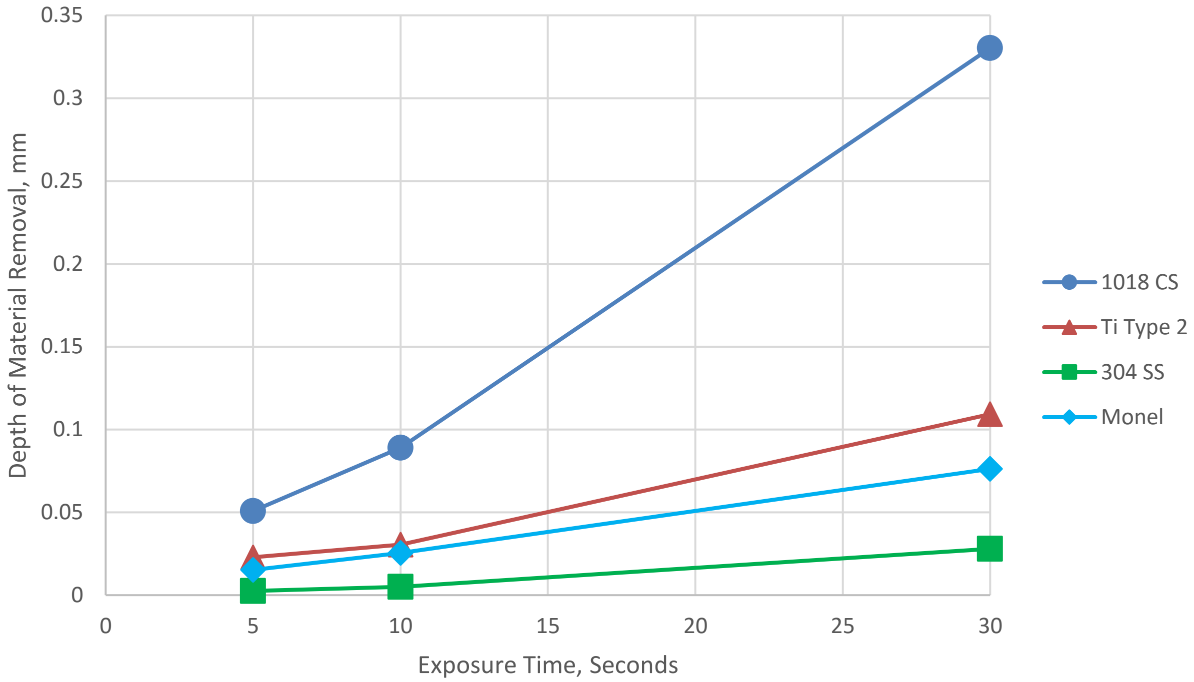
Copper 110, Copper-Nickel 90/10 and 1018 CS with Rotating Head at 103 MPa (15,000 psi)
Figure 8.



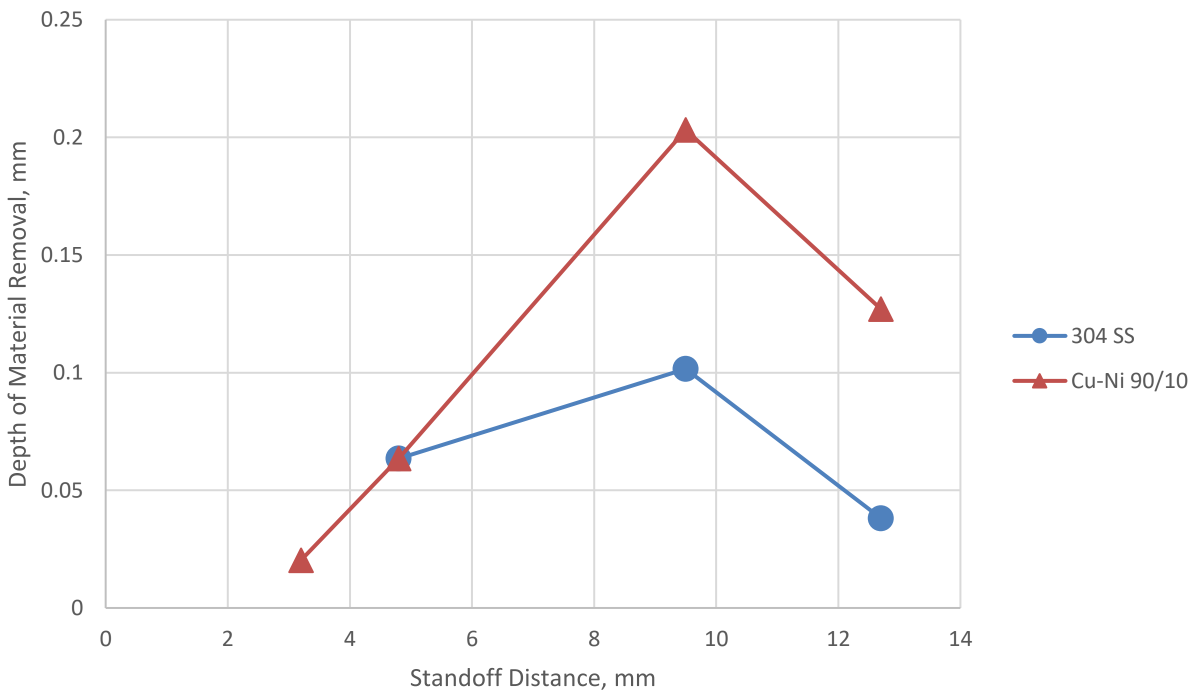
Monel, 304 SS, 1018 CS and Titanium with Rotating Head at 103 MPa (15,000 psi)
Figure 9.



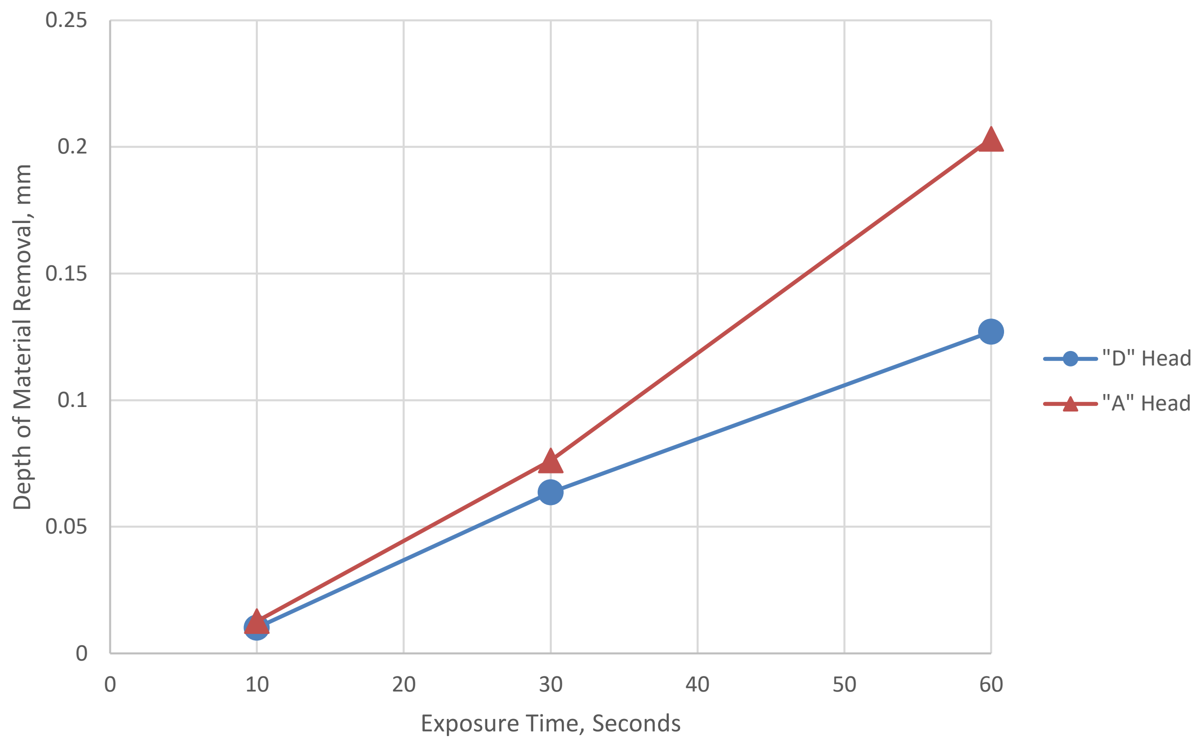
Monel, 304 SS, 1018 CS and Titanium with Rotating Head at 138 MPa (20,000 psi)
Figure 10.



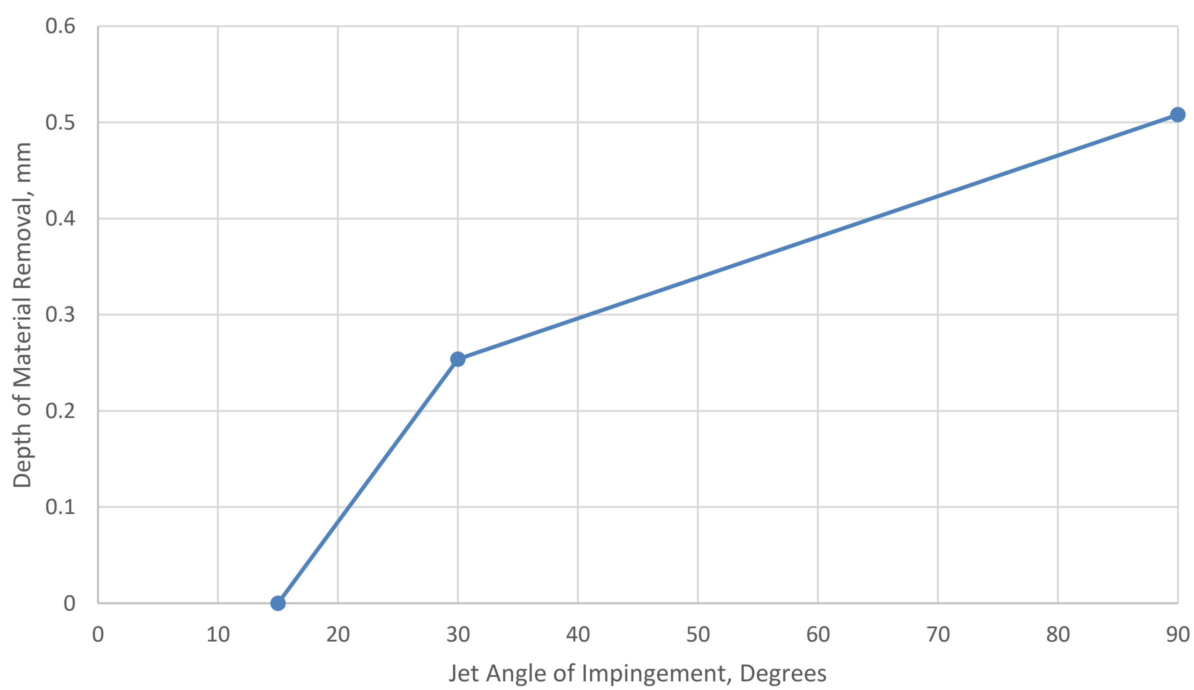
Monel, 304 SS, 1018 CS and Titanium with Rotating Head at 228 MPa (33,000 psi) at Exposure Times of 5, 10 and 30 Seconds
Figure 11.



The Effect of Standoff Distance on Material Removal in 304 SS at 138 MPa (20,000 psi) and Copper-Nickel 90/10 at 69 MPa (10,000 psi) at 30 Second Exposure Times
Figure 12.



The Effect of Increasing Flow Rate in 1018 CS at 138 MPa (20,000 psi)
Figure 13.



The Effect of Jet Angle of Impingement at 138 MPa (20,000 psi) in Copper 110 Plate
Figure 14.

The Result of 100 Passes with Rotating Head at 103 MPa (15,000 psi) in Copper 110 Plate
Figure 15.

The Result of 50 Passes with Rotating Head at 228 MPa (33,000 psi) in 1018 CDF Plate
Figure 16.

The Result of 50 Passes with Rotating Head at 228 MPa (33,000 psi) in Monel 400; Note Damage at End of Travel Range Where Pause of Direction Change Occurs
Figure 17.

The Result of 50 Passes with Rotating Head at 228 MPa (33,000 psi) in Titanium
Figure 18.