

ANNULAR EROSION FOOTPRINT UNDER STATIC ULTRASONIC PULSATING WATER JET EXPOSURE

**ALICE CHLUPOVA^{1*}, AKASH NAG², GABRIEL STOLARIK³, JAKUB
POLOPRUDSKY¹, SERGEJ HLOCH^{2,3}**

¹Institute of Physics of Materials, the Czech Academy of
Sciences, Brno, Czech Republic

²Institute of Geonics, the Czech Academy of Sciences, Ostrava,
Czech Republic

³Faculty of Manufacturing Technologies TUKE with a seat in
Prešov, Slovak Republic

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chlupova@ipm.cz

This paper examines an unusual annular erosion footprint observed during static exposure of metallic surfaces to an ultrasonically excited pulsating water jet (PWJ). The morphology is characterized by a comparatively preserved central region surrounded by a ring-shaped erosion zone, indicating that cumulative erosive loading is preferentially distributed away from the jet centerline. Circular and crescent-shaped footprints are considered as reference morphologies to illustrate different spatial distributions of PWJ-induced erosion. The annular footprint is interpreted as evidence of peripheral loading rather than direct evidence of a hollow-cone liquid structure, because several mechanisms may contribute to its formation. A hollow-cone-like impact structure remains one possible hypothesis requiring direct experimental verification. Static PWJ exposure can thus reveal spatial characteristics of erosive loading that may be obscured under dynamic traverse conditions. Recognizing such non-uniform impact regimes may improve control of PWJ surface treatment and provide useful guidance for optimizing nozzle and acoustic-system design where a defined spatial distribution of erosive loading is required.

KEYWORDS

Pulsating water jet, Erosion pattern, Annular erosion footprint, Morphology, Scanning electron microscopy

1 INTRODUCTION

Liquid impact erosion has long been studied primarily as an undesirable degradation mechanism affecting components exposed to repeated liquid loading [Hancox and Brunton 1966], including turbine parts [Ahmad et al. 2018], aerospace structures, and energy-related systems [Keegan et al., 2013]. At the same time, controlled jet-based technologies have shown that the same physical principles can also be exploited beneficially for surface treatment such as peening [Kumar et al. 2019], [Siahpour et al. 2023], [Siahpour et al. 2024], roughening [Ibrahim et al. 2023], [Stolárik et al. 2023], [Klichova et al. 2023], residual-stress engineering [Kumar et al. 2019], [Srivastava et al. 2019], [Siahpour et al. 2022], and localized material removal [Fard et al. 2025], [Wang et al. 2023]. Accordingly, ultrasonically excited pulsating water jet (PWJ) technology [Vijay et al. 1994] is especially attractive because it delivers high-frequency impacts [Foldyna and Svehla 2008], [Foldyna and Svehla 2011] in a spatially controlled manner and can therefore be used efficiently. In PWJ treatment, the physical meaning of the surface footprint is particularly important because it reflects not

only damage accumulation but also the organization of the impacting liquid body itself.

The research focused on PWJ emphasized performance under machining [Raj et al. 2019] and disintegration applications [Foldyna et al. 2005] [Riha et al. 2021], [Lehocka et al. 2020], where dynamic traverse conditions are employed [Hela et al. 2010]. Although conditions such as traverse speed [Nag et al. 2026] or overlapping factor [Stolarik et al. 2026] are technologically relevant, they create erosion grooves or homogeneously roughened areas that tend to mask the geometry of local erosion sites. The erosion footprint must be considered not merely as a passive damage trace, but also as a possible surface record of the mechanical structure of the water jet at the point of impact with a solid substrate. Therefore, static exposure at a fixed stand-off distance, providing single erosion craters, is especially valuable, as it allows the local footprint to be resolved directly and more clearly related to the impact regime acting on the surface [Poloprudský et al. 2021]. This issue becomes particularly important when the impacting liquid droplet or slug departs from the simplified picture of a compact droplet or an axisymmetric jet packet [Foldyna et al. 2009].

In the broader fluid-mechanical literature, annular morphologies of sprays and atomized liquids are well known. Generally, an annular or corona-shaped erosion footprint, typical for hollow-cone-jet regime, is created intentionally using a special design of nozzles, such as axial or tangential swirl injectors, where cone spray is formed through the internal swirl motion of the liquid [Som and Mukherjee 1980], [Vijay et al. 2015], [Zheng et al. 2020], spiral design nozzle, where the fluid is impacted on a protruding spiral shape breaking it apart [Kristof et al. 2019], or last but not least deflector pin design, where a central pin diverts the flow direction of the jet [Lefebvre and McDonell 2017]. These studies do not describe the same physical system as ultrasonic PWJ erosion and should not be treated as direct proof of the mechanism considered here. Their relevance lies mainly in showing that non-compact and annular liquid-discharge configurations are physically plausible and can be highly sensitive to forcing conditions, geometry, and flow stability. In our case, the mechanism of creation is different, although the erosion footprint of the corona shape can be similar.

In the present study, we observed an unusual annular manifestation under static ultrasonic PWJ exposure of AISI 316L, consisting of an erosion footprint with a preserved central core surrounded by a ring-shaped eroded zone. Compared with a conventional circular erosion site, this morphology suggests that the dominant erosive loading may have been shifted away from the centerline toward a peripheral annular zone. The interpretation is intentionally conservative: the present work does not claim direct optical verification of jet geometry; rather, it highlights a surface signature that may point to an underexplored PWJ operating mode.

The novelty of the present contribution is not the first observation of an annular footprint itself. Rather, this study focuses on the morphology of this unusual erosion pattern and examines it systematically in comparison with conventional circular and asymmetric crescent-shaped PWJ footprints. The annular footprint is a surface indicator of spatial redistribution of erosive loading toward a peripheral region. The hollow-cone configuration is presented only as one possible interpretation requiring direct experimental verification.

2 EXPERIMENTAL BACKGROUND

The present contribution does not introduce a completely new experimental campaign; instead, it re-examines selected

observations from our earlier studies from a morphology-oriented perspective, emphasizing the possible relation between erosion-footprint shape and annular impact loading, and combines them with results on tantalum and 316L stainless steel. This paper is intentionally limited to the morphology of single erosion craters formed using PWJ technology under static-jet exposure and focuses mainly on cases where the corona-shaped footprint appears. The purpose is not to establish a complete hydrodynamic model of jet formation. The aim is to show that static exposure can reveal locally informative impact signs whose geometry may contain mechanistically relevant information about the spatial distribution of erosive loading, as reported also in [Sun et al. 2026].

In recent work using PWJ on aluminum [Hloch and Poloprudsky 2025], which used an extended tubular nozzle, a corona-shaped erosion footprint was observed under certain conditions but was not discussed. Similarly, detailed observation of the presented topography of results published in work on aluminum and copper [Hloch and Svobodova 2024] confirmed the occurrence of annular erosion marks created by specific PWJ parameters, not by a special nozzle design, but by employing a standard cylindrical nozzle. However, this annularity was not addressed as a separate phenomenon.

PWJ experiments on 316L steel and Ti6Al4V alloy, published in [Poloprudský et al. 2021], showed a crescent-shaped pattern of erosion footprints under static exposure at a fixed effective stand-off distance [Poloprudsky et al. 2024], as exposure time increases, using the standard cylindrical nozzle. Preparatory work related to the PWJ experiments on tantalum [Nag and Hvizdos 2021] also highlighted this research gap.

The main parameters directly relevant to the present interpretation are summarized here:

- For the reference circular footprint (see Fig. 1), the PWJ exposure on aluminum alloy was carried out under the following conditions: $p = 15$ MPa, $f = 20$ kHz, $d = 0.3$ mm, $lc = 12$ mm, $z = 5$ mm, $Q = 0.66$ l/min, nozzle = standard Hammelmann circular nozzle, number of repetitions = 3, surface preparation = mechanical grinding on SiC papers followed by polishing using diamond polishing paste to $0.25\ \mu\text{m}$, with the final step being polishing in an oxidic polishing suspension.
- The crescent-shaped footprint formed on technically pure copper (see Fig. 2) was created by PWJ at: $p = 20$ MPa, $f = 40$ kHz, $d = 0.6$ mm, $lc = 10$ mm, $z = 23$ mm, $Q = 3.06$ l/min, nozzle = standard Hammelmann circular nozzle, number of repetitions = 5, surface preparation = mechanically ground using SiC papers followed by mechanical polishing using diamond polishing paste, with final step being electrolytic polishing.
- The corona-shaped footprint forming the main subject of this contribution was observed for AISI 316L (see Fig. 3) under static exposure at $p = 50$ MPa, $f = 20$ kHz, $d = 0.6$ mm, $lc = 18$ mm, $z = 34$ mm, $Q = 4.83$ l/min, nozzle = standard Hammelmann circular nozzle, number of repetitions = 4, surface preparation = mechanically ground using SiC papers followed by mechanical polishing using diamond polishing paste, with the final step being electrolytic polishing.

Other details of the PWJ, including equipment, experimental setup, and operating conditions, can be found in our previous papers [Hloch et al. 2025], [Hloch et al. 2024], [Poloprudský et al. 2021]. All the samples were observed using a Tescan Lyra at an accelerating voltage of 10kV using a secondary electron detector. The present experiments do not allow us to establish a quantitative, material-dependent threshold for forming circular, crescent-shaped, or annular footprints. Hardness, yield strength, strain-hardening behavior, and ductility can influence the threshold at which a given spatial distribution of PWJ loading becomes manifested as permanent surface deformation or

material removal. More ductile materials may accommodate repeated impact loading through plastic deformation, pile-up formation, and lateral displacement before extensive material removal occurs, whereas harder or higher-strength materials may require a higher local impact intensity or a larger number of impacts to develop a clearly distinguishable erosion footprint.

3 RESULTS AND DISCUSSION

In this contribution, we first briefly recall two reference erosion footprints: circular and crescent shapes, which serve mainly as reference morphologies against which the corona-shaped footprint can be compared and placed in morphological context. Data presented in Fig. 1 and 2 originate from previously acquired observations of erosion morphologies, re-examined here as reference cases for comparison with the annular footprint. Fig. 3 presents new data. The contribution therefore focuses on comparative morphological interpretation rather than presenting all datasets as newly acquired experimental results.

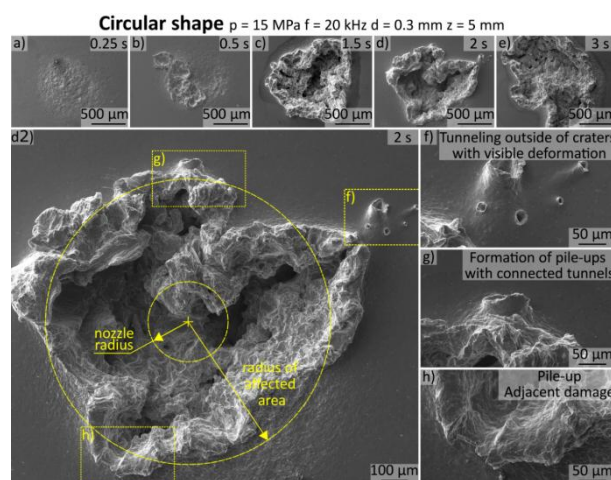


Figure 1. Formation of circular erosion pattern on aluminum alloy based on exposure time and typical details selected from 2s exposure

The most common erosion pattern, formed on the metal surfaces under static exposure to PWJ, is a conventional circular footprint, similar to that observed in Fig. 1 for aluminum alloy. This erosion pattern develops concentrically with exposure time, resulting in a deep, well-defined crater with a central material-removal region surrounded by an extrusion zone (pile-up [Stolarik et al. 2025]). This morphology consists of a relatively symmetric distribution of impact loading around the jet axis. Local pile-up formation and subsurface hydrodynamic micro-tunneling [Fujisawa 2022], [Chlupova et al. 2023] can also be observed in the surrounding region, confirming that even the conventional circular footprint contains a complex combination of direct erosion, lateral flow effects [Fujisawa 2022], and subsurface damage evolution [Chlupova et al. 2023], [Poloprudský et al. 2025].

The crescent-shaped footprint is a second reference case, represented by erosion craters formed on technically pure copper (Fig. 2) [Chlupova et al. 2025]. Compared with the circular case, this phenomenon is less common; however, it receives little attention because it is often attributed to misalignment between the jet axis and the eroded surface. The morphology of the crescent pattern is clearly asymmetric, characterized with localized material removal in an arc-like region bordered by an outer extrusion zone. The detailed views show deep valleys, cracks, undercutting, roughening, and severe plastic deformation. [Hloch et al. 2024] report all these fractography features as associated with subsurface hardening. Similarly to

the circular erosion pit, there are also signs of lateral outflow [Fujisawa 2022] and subsurface microchannel formation [Hloch et al. 2022]. This footprint is therefore interpreted as an example of non-uniform impact loading, in which the delivered erosive energy is spatially redistributed rather than concentrated symmetrically about the nozzle axis.

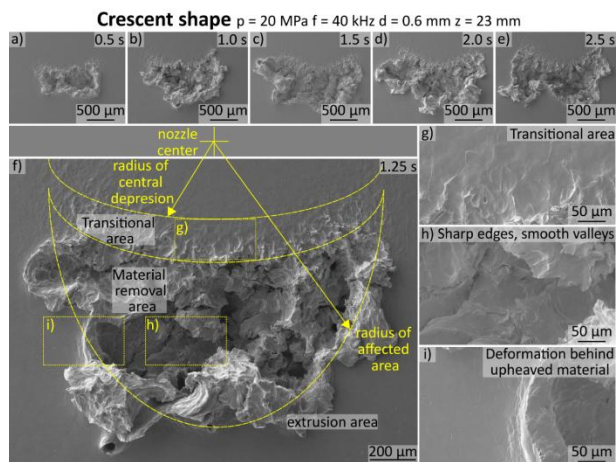


Figure 2. Formation of crescent erosion pattern on technically pure copper based on exposure time and details of typical morphological features observed in the exposure range of 0.5-2.5 s.

The main topic of the present work is the intentionally and systematically investigated morphology of the corona-shaped erosion footprint under static exposure of AISI 316L (Fig. 3) to ultrasonically excited PWJ. In contrast to the conventional circular footprint, the eroded region forms a ring-like annulus surrounding a preserved central core.

The time sequence in the upper part of Fig. 3 shows that this morphology develops progressively with exposure time and stabilizes into a well-defined corona-like pattern. The main micrograph in Fig. 3, showing corona erosion after 15 s of exposure, reveals a distinct annular erosion zone bounded by pile-ups at the outer edge.

The central region remains comparatively preserved, without visible erosion at the applied SEM observation scale, whereas a gradual transition toward the severely eroded annular region is observed.

High-magnification observation of the central area confirms that the original surface topography is preserved there, with only a gradual transition toward the eroded annular region. The significantly eroded parts of the corona are locally smoothed by lateral flow, whereas the outer boundary of the whole erosion crater is marked by pronounced material displacement and pile-up formation.

Based on the observed morphology, the corona-shaped footprint is interpreted primarily as a surface manifestation of peripheral annular loading. However, the erosion footprint alone does not uniquely determine the instantaneous geometry of the impacting liquid body. Several mechanisms may potentially contribute to such a spatial distribution of erosion. These include off-axis maxima in impact pressure and shear stress, radial or lateral outflow following impact, jet wandering, air entrainment, i.e., the effects that weaken or partially deplete the central jet core. In an ultrasonically excited PWJ, these effects may additionally interact with pressure pulsations, acoustic-chamber tuning, resonance conditions, jet breakup, and the evolution of individual liquid structures between the nozzle exit and the target.

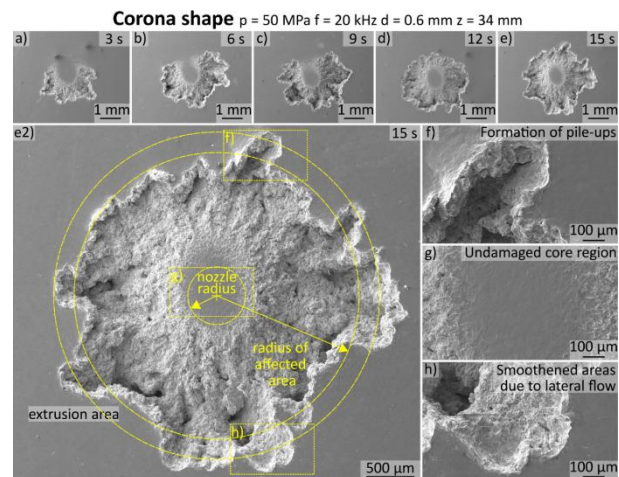


Figure 3. Formation of corona erosion pattern on austenitic stainless steel AISI 316L based on exposure time and typical details selected from 15 s exposure.

Experimental evidence demonstrates a redistribution of erosive loading toward a peripheral annular region, as inferred from the ring-shaped erosion footprint and comparatively preserved central region. It does not directly demonstrate the existence of a hollow-cone liquid structure. A hollow-cone-like liquid structure is only one possible hypothesis that requires direct visualization [Zelenak et al. 2015] for verification.

Within the context of PWJ technology, a plausible explanation is that this regime originates from acoustic-flow interactions specific to ultrasonic operation, including acoustic-chamber tuning, resonance effects, cavitation-assisted depletion of the jet core, air–water interactions, or axial redistribution of flow within the nozzle.

It is worth noting that possible hydrodynamic mechanisms are alternative hypotheses rather than established explanations. To prove this, direct high-speed visualization and synchronized pressure/force measurements are necessary.

A complementary future route for identifying PWJ operating regimes could use vibration or acoustic-emission signals. Ganovska et al. [Ganovska 2016] showed in AWJ machining that these accompanying signals can support on-line monitoring and, together with artificial neural networks, prediction and control of process outcomes. By analogy, vibro-acoustic signatures from an ultrasonically excited PWJ may contain information on changes in the organization of the impacting liquid structures. When calibrated against high-speed visualization and erosion-footprint morphology, neural-network models could potentially classify compact, asymmetric, and annular regimes and help tune pressure, excitation frequency, acoustic-chamber length, flow rate, and stand-off distance toward a desired PWJ structure. Such an approach could provide a non-invasive diagnostic and design tool, although its applicability to PWJ remains to be experimentally demonstrated.

The observation is particularly noteworthy because it was obtained using a conventional cylindrical nozzle configuration, indicating that annular impact loading may arise not only from intentionally engineered swirl-type nozzles but also from resonance-controlled flow reorganization within an acoustically tuned system, as reported by Liu [Liu et al. 2026]. Nevertheless, the proposed interpretation remains hypothetical, and the exact formation mechanism requires direct experimental verification. Although it does not constitute direct evidence of the same phenomenon, the broader literature supports the physical plausibility of the corona-jet interpretation. In atomization science, hollow-cone and cone-jet regimes are well-established liquid-discharge modes, typically generated by swirl-induced

rotation or strongly forced flow conditions [Duronio et al. 2026]. Similarly, self-excited pulsed nozzles [Riha et al. 2026], [Szada-Borzyszkowska et al. 2023] demonstrate that a nominally continuous inflow can reorganize into temporally oscillatory jet structures. These examples illustrate that annular liquid-body configurations are physically feasible and highly sensitive to nozzle geometry and operating conditions.

A PWJ-specific explanation may be associated with the way the ultrasonic system is tuned by the acoustic chamber length setting. Previous studies have shown that the operating frequency and transmitted power depend strongly on the interaction between water flow rate, nozzle diameter, and chamber length, as these parameters influence the effective hydraulic impedance and standing-wave conditions within the system [Nag et al., 2021]. Earlier investigations further demonstrated that pressure pulsations are generated upstream of the nozzle, propagate through the liquid waveguide, and are amplified under resonant conditions, with jet breakup into discrete pulses occurring only after a certain standoff distance from the nozzle exit [Riha and Foldyna 2012], [Foldyna et al. 2007]. This mechanism is also consistent with patented PWJ architectures in which acoustic pulsations are generated in a resonant chamber, mechanically amplified, and transmitted through a liquid waveguide to the nozzle system [Nag et al. 2019]. Under such conditions, the acoustic field may progressively redistribute liquid delivery away from the centerline, weaken the jet core, and promote annular impact loading, ultimately producing the observed corona-shaped footprint.

This observation is significant because it was recorded using standard cylindrical nozzles [Hloch and Poloprudský 2025], without a dedicated swirl chamber. The results, therefore, suggest that an annular erosion footprint in PWJ may emerge not only from swirl-induced liquid rotation but also from resonance-driven acoustic-flow interactions within a tuned ultrasonic system [Foldyna and Svehla 2008]. Importantly, the present evidence is derived from erosion morphology rather than direct visualization of the jet itself [Hloch et al. 2025]. This distinction makes the finding particularly relevant to PWJ research, as it demonstrates that static ultrasonic exposure can reveal mechanistically informative impact signatures that may remain obscured during conventional experiments with a traverse movement of the jetting head [Lehocka et al. 2021].

4 CONCLUSIONS

Static ultrasonic PWJ exposure revealed a distinct annular erosion morphology characterized by a comparatively preserved central region surrounded by a strongly eroded peripheral zone. Comparison with conventional circular and asymmetric crescent-shaped footprints demonstrates that PWJ-induced erosion can exhibit markedly different spatial distributions of cumulative loading. The annular footprint provides evidence for preferential peripheral loading but does not, by itself, establish the geometry of the impacting liquid structure. Possible explanations include off-axis pressure and shear-stress distributions, lateral outflow, jet wandering or instability, air entrainment, weakening of the central jet core, and potentially a hollow-cone-like impact configuration. Discrimination between these mechanisms requires direct time-resolved visualization, backlighting imaging, shadowgraphy, and synchronized pressure or force measurements. Static exposure is therefore particularly useful as a diagnostic approach for identifying spatially heterogeneous PWJ impact regimes.

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DATA AVAILABILITY

Data related to the paper are available in the Zenodo repository with <https://doi.org/10.5281/zenodo.21339043>.

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CONTACTS:

Ing. Alice Chlupova, Ph.D.
 Structural Integrity of Cyclically Loaded Materials, Institute of Physics of Materials AS CR, v. v. i.
 Zizkova 513/22, Brno, 616 00, Czech Republic
 +420 532 290 366, chlupova@ipm.cz

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