Numerical simulation of cavitation behavior and peening experiments in cavitation peening processing

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Abstract. The software, Fluent, was used to analyze the cavitation behavior of the submerged water jets generated by contraction nozzle, angle nozzle and organ pipe nozzle. Angle nozzle was chosen for cavitation peening based on the results of numerical simulation. The cavitation peening experiments for aluminum alloy 2A12 were conducted with the different processing parameters. The surface roughness, residual stress distribution and morphology of the treated sample surface were investigated. Results show that the distribution of strengthening area is consistent with that of simulated cavitation bubbles cluster. Using the optimized parameters, the surface residual compressive stress and its depth reach the maximum values of 320MPa and 390μm, respectively, which were increased nearly 2.7 times and 5.5 times than those of the original sample, respectively, while the corresponding surface roughness was only 1.29μm, which was much smaller than that of conventional shot peening.

1. Introduction
In cavitation peening(CP), a high speed submerged water jet with cavitation bubbles cluster blow the surface of metal [1]. The high-pressure shock waves and high-speed microjets generated when the cavitation bubbles collapse near the solid boundary can be used to strengthen the surface of metals. As there are no collisions with solid bodies, the increase in roughness is much smaller than that produced with traditional shot peening [2]. Cavitation peening suppresses hydrogen embrittlement which is sensitive to surface roughness [3]. It can be used in deep and narrow regions where the stress is more concentrated, as demonstrated in the increase in the gear lifetime [4] and the element in a continuously variable transmission belt [5]. Cavitation nozzle is the core component in the cavitation peening processing, which produces the high speed submerged water jet that contains a large number of cavitation bubbles. Guan et al [6] used Mixture model, Singhal cavitation model and RNG κ-ε turbulence model to simulate the cavitation nozzle and found that the optimal initial diameter of the cylindrical section was 1mm. Zhao et al [7] used Fluent to simulate the internal cavitation behavior of angle nozzle, the results showed that due to the combined effect of reflux and pressure, the expansion angle has an optimum value for the formation rate of cavitation bubbles; when the expansion angle is between 40° and 60°, the smaller the expansion angle is, the better the cavitation effect is. H. Soyama et al [8] investigated the effect of various types of nozzle geometries on the cavitation ability and found that organ pipe nozzle has better cavitation ability than the nozzles modified based on it.
This paper uses Fluent to simulate the cavitation behavior of contraction nozzle, angle nozzle and
organ pipe nozzle used in the cavitation peening processing based on the renormalized group RNG $\kappa$–$\varepsilon$
turbulence model and Singhal cavitation model. The aluminum alloy 2A12 samples were strengthened
using the nozzle with the best cavitation ability. By analyzing the surface roughness, residual stress
distribution and surface morphology of the samples in the cavitation peening experiments, the effects of
standoff distance and cavitation time on the surface quality of the metal material are obtained, which
provide a reference for the optimization of actual processing parameters.

2. Numerical Simulation

2.1. Model establishment

The structural schemes of three nozzles are shown in Fig.1 and Table.1. They include entrance diameter
D, resonant cavity diameter B, throat diameter d, throat length l, dilation section diameter E, dilation
angle $\theta$, dilation section length L and contractile angle $\alpha$. In order to reduce the interference factors
during the comparison of the cavitation ability of various types of nozzles, the dimensions at the critical
structure of the three nozzles shown in the Fig.1 are all taken as the same value without affecting the
substantial cavitation ability of the nozzles. According to the actual size of the tank used in the
experiment, the size of the external flow field is set to 0.08 m $\times$ 0.1 m.

![Fig 1. Nozzle structure diagram: (a) Contraction nozzle, (b) Organ pipe nozzle and (c) Angle nozzle.](image)

### Table 1. Nozzle structure parameters.

|                      | D/mm | B/mm | d/mm | l/mm | E/mm | $\theta$/° | L/mm | $\alpha$/° |
|----------------------|------|------|------|------|------|-----------|------|-----------|
| Contraction nozzle   | 16   | 10   | 1    | 4    |      |           |      |           |
| Organ pipe nozzle    | 16   | 10   | 1    | 4    | 8    | 8         |      |           |
| Angle nozzle         | 16   | 10   | 1    | 4    | 30   | 8         | 13.5 |           |

Given the symmetry in 2D axial plane, the physical model can be simplified in a 2D axisymmetric
model. The half-flow field mesh of angle nozzle is shown in Fig.3 and the mesh of other two nozzles
are similar to that of angle nozzle. The nozzle inlet is set to pressure inlet, the peripheral boundary to
the wall, and the flow field outlet to the pressure outlet. The mesh near the nozzle exit and wall are
increased to guarantee the precision while the whole quantity of each mesh is about 180000.
In this study, a stationary single-phase fluid is assumed under the initial condition. Both inflow and outflow boundaries are modeled as constant-pressure surfaces. Thus, a converged or near converged solution for a single-phase liquid flow is obtained. For the present computations, the Singhal cavitation model [9] is used for it can easily yield a converged result and the renormalized group RNG $\kappa-\varepsilon$ is adopted with standard wall function to calculate the cavitation flow field [9]. The boundary conditions of the wall are impermeability and no-slip for velocity. The normal gradient of pressure is assumed to be zero. The inlet boundary condition is pressure inlet, 20MPa, and the outlet boundary condition is pressure outlet, 101325 Pa. The turbulence intensity of pressure inlet and pressure outlet are setted to 5%.

2.2. Numerical simulation results and analyses

2.2.1. Distributions of velocity and pressure. Velocity distributions of the submerged water jets generated by the three kinds of nozzles are shown in Fig.3. In Fig.3(a) and (b), when the internal water flow of the nozzles passes through the resonant cavity, the formed speed transition areas are small because the cross-sectional areas of nozzles reduce drastically. However, the angle nozzle shown in Fig.3(c) forms a more pronounced speed gradient in the contracted section due to the cross-sectional area decreases regularly. The jet impact region of the angle nozzle has a relatively pronounced pulsation at $X=0.06m$ and $0.08m$, while a small pulsation occurs at $X=0.047m$ for organ pipe nozzle. The occurrence of uneven flow rates and pulsations in the jet impact regions is due to the presence of “necking”. The relatively concentrated cavitation bubbles together with the vortex caused by the shear effect between the impact jet and static water lead the fluid to produce a Y-direction velocity, which finally forms a local “necking” phenomenon. Fig.4 and Fig.5 show the axis velocity curves and pressure curves of nozzles, respectively. Combined with Fig.3, it can be found that angle nozzle and organ pipe nozzle can create a wider range of jet impact region than that of contraction nozzle due to the presence of expansion sections. The vertical-lateral maximum isokinetic core area of the angular nozzle is much larger than that of the other two types of nozzles, covering an area of 0.04m to 0.10m in the X axis direction, while a larger isokinetic core area represents a larger low-pressure area which is conducive to the growth and development of cavitation nucleus and the formation of cavitation bubbles cluster.
Fig 3. Distributions of velocity in three different nozzles: (a) Contraction nozzle, (b) Organ pipe nozzle and (c) Angle nozzle.

Fig 4. Axial velocity curves.
2.2.2. Distributions of the vapor-phase volume fraction. From Fig.6(a), it can be seen that cavitation firstly occurs on both sides of the throat boundary at the inlet of the throat of contraction nozzle. Then as the value of the X-axis increases, vapor-phase volume fraction gradually decreases and almost disappears when it reaches the throat outlet. As can be seen from Fig.6(b), the cavitation also appears in the expansion section of the organ nozzle due to the vortex caused where the high-speed jet enters the expansion section and shear the low-speed water in the small area. The particularity of the vortex flow makes the surrounding cavitation nucleus grow into the center of the vortex core and develop into cavitation bubbles. With the continuous accumulation of cavitation bubbles in the expansion section, the vapor-phase volume fraction reaches the maximum at the boundary layer of the expansion section, with a peak value of 0.95. The stage II and stage III in Fig.6(b) show the periodic cavitation weakening phenomenon caused by a periodic pulsation. During those stages, the backflow of external environment water quickly fills the area occupied by the disappeared cavitation bubbles in the expansion section, resulting in a large attenuation of the vapor-phase volume fraction distribution area.

Unlike the cavitation of the abovementioned nozzles, the cavitation of angle nozzle first appears near the boundary of the wall at the junction of throat outlet and expansion section. The contraction section of the angle nozzle can form a relatively regular speed increase gradient, so that no jet bulge similar to the abovementioned nozzles occurs at the inlet of the throat. When the jet flows into the expansion section, the high-speed columnar jet winds up the local water at the joint between the expansion section and the throat to form an annular vortex and shear the low-speed water in expansion section to form a coherent vortex. These vortices cause the surrounding cavitation nucleus to grow into cavitation bubbles in the low-pressure region of the center of the vortex core. The vapor-phase volume fraction distribution of ring-shaped cavitation bubbles cluster has an obvious gradient change and finally distributes in a flaming manner, with a peak value of 0.97. The volume of the cavitation bubbles cluster of angle nozzle is much larger than that of organ pipe and there is no periodic reduction. From the standpoint of improving the effectiveness of cavitation peening, angle nozzle is most suitable because it can continuously and stably output a wider range of cavitation bubbles cluster with higher vapor-phase volume fraction than those of the abovementioned nozzles.
(a) Stage I
(a) Stage II

(b) Stage I
(b) Stage II
(b) Stage III
(c) Stage I
3. Cavitation peening experiments

3.1. Experimental setup

The peening experiments were conducted with the cavitation peening system shown in Fig. 7. During the experiment, the test water was pressurized by a plunger pump and injected through the test nozzle. Then the water jet flowed vertically downward into a transparent water tank full of water. The distance between the target surface and the nozzle outlet section was accurately modified through a screw mechanism. The angle nozzle used in the experiment is identical to its counterpart devoted to the numerical simulation. Cylindrical aluminium alloy 2A12 samples, 40mm in diameter and 3mm in thickness, served as target samples, which were fixed and submerged at the bottom of tank by a clamp, as shown in Fig. 7. The detailed processing parameters of the cavitation peening are listed in Table 2.
Table 2. Processing parameters of the cavitation peening

|                      | A  | B  | C  | D  | E  | F  | G  | H  | J  | K  |
|----------------------|----|----|----|----|----|----|----|----|----|----|
| Standoff distance S/mm| 20 | 30 | 40 | 50 | 70 | 40 | 40 | 40 | 40 | 40 |
| Cavitation time T/min | 4  | 4  | 4  | 4  | 4  | 1  | 2  | 4  | 6  | 10 |
| Injection pressure P/MPa | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |

3.2. Experiments results and analyses

3.2.1. Surface roughness. Fig.8(a) shows the roughness curve of samples with different standoff distances. The roughness value shows a sharp tower distribution, indicating that cavitation peening has the best standoff distance. The surface roughness first increases with the standoff distance, and then decreases rapidly. When the standoff distance increases to 40mm, the surface roughness increases greatly to a maximum value of 1.29μm. It shows that the cavitation bubbles in the submerged water jet are fully developed at this standoff distance, and gradually collapse due to the stagnation pressure near the sample surface, which makes the sample surface undergo a strong plastic deformation. Such plastic deformation reduces rapidly after the standoff distance exceeds the optimal collapse distance of the cavitation bubbles cluster, so the roughness decreases rapidly at this process. Fig.8(b) shows the roughness curve of samples with different cavitation times. In the initial stage, the surface roughness increases slowly with cavitation time. When the cavitation time reaches to 4 min, the surface roughness enters a short period of approximate plateau because the degree of plastic deformation of the surface layer has become saturated. With the prolonged cavitation time, the surface roughness of the sample rises sharply, which is not cavitation peening but cavitation erosion.

Fig 8. Roughness curves of aluminum alloy 2A12 samples: (a) with different standoff distances, (b) with different cavitation times.
3.2.2. Distribution of residual stress field. As shown in Fig.9(a), the residual compressive stress and its influence depth vary with standoff distances. When the standoff distance is increased to 40mm, the maximum surface residual compressive stress is greatly improved to 320MPa, 2.7 times higher than that of the original sample. At the same time, the influenced depth of the residual compressive stress also reaches a maximum value of about 390μm, 5.5 times higher than that of the original sample. The surface residual stress and its influenced depth show a drastic change with the extension of the standoff distance, while in Fig. 5(b) those two parameters increased smoothly with the prolongation of the cavitation time and maintain a relatively stable state over a certain time. When the cavitation time is controlled between 4min and 6min, the maximum surface residual compressive stress and its influenced depth fluctuate between 310MPa ~ 320MPa and 390μm ~ 400μm, respectively.

However, when the cavitation time is extended to 10min, there is almost no residual compressive stress on the sample surface, and even residual tensile stress is present on the local surface. Thus, in the cavitation time domain of 4min ~ 6min, the surface residual compressive stress and its influence depth do not change much. If the cavitation time is not properly controlled, the surface residual compressive stress and its influence depth will rapidly drop as shown in Fig.8(b). This is because the originally formed strengthening layer of the material is etched away due to the repeated impacts of high-pressure shock waves and high-speed microjets.

![Distribution of residual stress field of aluminium alloy 2A12 samples](image)

Fig 9. Distribution of residual stress field of aluminium alloy 2A12 samples: (a) with different standoff distances, (b) with different cavitation times.

3.2.3. Surface Macro-Micromorphology. The original sample shown in Fig.10(a) has a smooth and clean surface, with no obvious plastic deformation. While the sample shown in Fig.10(b), which is peened by the processing parameter A, has a circular plastic deformation strengthening area with matte color. The cavitation bubbles cluster formed by the angle nozzle exhibits an approximately annular distribution and will diffuse from the center of the jet along the surface of the sample at a certain speed when the submerged water jet is blocked by the sample, then continuously collapse in the high-pressure region. These two effects generate an annular strengthening area as shown in Fig.10(b).
Fig 10. Macroscopic morphology of aluminum alloy 2A12 before and after CP: (a) Original sample, (b) Processing parameter A.

Fig.11 shows the scanning electron microscope images of a surface sample peened at variable cavitation time when the injection pressure and standoff distance are fixed at 20MPa and 40mm, respectively. The original sample surface shown in Fig.11(a) is smooth and flat. In Fig.11(b) and (c), irregular fluctuating can be observed on the surface of the sample, which indicates that severe plastic deformation occurs in the strengthening area, without damaging the sample surface. Obviously, the plastic deformation can still be seen in Fig.11(d), and some white scattered dots appear in some positions because of the high-speed microjets generated when the cavitation bubbles collapse close to the wall, which indicates that as the cavitation time increases, the surface quality of the sample gradually deteriorates. However, the scattered dots caused by the impact of microjets alone do not damage the sample surface. With the high-pressure shock waves released by cavitation bubbles collapse repeatedly act on the sample surface, the surface structure is destroyed when the fatigue limit of the material is exceeded. As shown in Fig.11(e), a dark black pit appears after a long cavitation time, which means that the cavitation peening causes cavitation erosion on the sample surface. Fig.11(f) ~ (h) are partial enlarged views of the erosion area of Fig.11(e). In Fig.11(f), the erosion pits scattered on the surface of the sample, and mainly occur in the plastic deformation of the surface of the convex position. When these cavitation erosion areas are enlarged to 1000 times, it is found that the erosion pits are formed by many small cavitation pits as shown in Fig.11(f). The single cavitation pit is enlarged to 2200 times in Fig.11(h), jagged edge like metallurgical damage caused by fatigue failure of hard materials are observed. This reflects that the aluminum alloy 2A12 is strengthened by cavitation peening from the initial effective plastic deformation to the cavitation erosion.
Fig 11. SEM images of aluminium alloy 2A12 with different cavitation times: (a) Original sample, (b)2min, (c)4min, (d)6min and (e)–(f)10min.

4. Conclusion
The cavitation ability of the contraction nozzle is the most unsatisfactory. The organ nozzle can meet the need of cavitation peening, but the cyclic reduction of cavitation performance will adversely affect the utilization efficiency. The angle nozzle can continuously output a stable cavitation bubbles cluster which has relatively high vapor-phase volume fraction, covering a range of 0.04m~0.12m. Therefore, the angle nozzle can best meet the requirements of cavitation peening. At the same time, the strengthen area in the experiment agrees well with the distribution of cavitation bubbles cluster in the numerical simulation when the angle nozzle is used in the cavitation peening.

Cavitation peening has the best standoff distance and cavitation time. The optimized processing parameters in this experiment is P=20MPa, S=40mm and T=4min. Under this condition, the surface residual compressive stress and its influence depth reach the maximum value of 320MPa and 390μm, respectively, which were increased nearly 2.7 times and 5.5 times, respectively.

It was found that the sample surface was kept smooth during the peening period. Meanwhile, no sharp edges and micro cracks were found as in the conventional shot peening, which avoid stress concentration at these deformations. In addition, the surface damage caused by excessive cavitation peening mainly due to the fatigue damage caused by cavitation erosion, so the cavitation time must be controlled within a reasonable range.

Acknowledgments
The present work was supported by the National Natural Science Foundation of China (51575245, 51675234).

References
[1] Soyama H, Kusaka T, Saka M, Peening by the use of cavitation impacts for the improvement of fatigue strength, Journal of Materials Science Letters. 20 (2001) 1263-1265.
[2] Soyama H, Dan O M, Mall S, Compressive Residual Stress into Titanium Alloy Using Cavitation Shotless Peening Method, Tribology Letters. 17 (2004) 501-504.
[3] Takakuwa O, Soyama H, Suppression of hydrogen-assisted fatigue crack growth in austenitic stainless steel by cavitation peening, International Journal of Hydrogen Energy. 37 (2012) 5268-5276.

[4] Soyama H, Sekine Y, Sustainable surface modification using cavitation impact for enhancing fatigue strength demonstrated by a power circulating-type gear tester, International Journal of Sustainable Engineering. 3 (2010) 25-32.

[5] Soyama H, Shimizu M, Hattori Y, et al, Improving the fatigue strength of the elements of a steel belt for CVT by cavitation shotless peening, Journal of Materials Science. 43 (2008) 5028-5030.

[6] Guan J F, Deng S S, Guo G D, et al, Numerical simulation of internal flow field in angle nozzle for cavitation water jet, Machine Tool & Hydraulics. 40 (2012) 46-50.

[7] Zhao D X, W Q, Du M M, Fluent-Based numerical simulation of the cavitation behavior in the angle nozzle, Journal of Northeastern University (Natural Science). 37 (2016) 1283-1287.

[8] Soyama H, Effect of nozzle geometry on a standard cavitation erosion test using a cavitating jet, Wear. 297 (2013) 895-902.

[9] Ansys, Inc, “ANSYS Fluent Theory Guide.” Release 17.0, 2016.