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Optimization of surface quality for YG20 tungsten steel cut by liquid nitrogen assisted abrasive suspension jet

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Abstract

Liquid nitrogen assisted abrasive suspension jet (LN₂-ASJ) is a hybrid machining method that performs pre-cooling prior to cutting, which has high cutting efficiency for hard and brittle metals. Hard and brittle metals often have both ductile and brittle fracture areas on the cut surface, and the surface quality is poor during LN₂-ASJ one-time forming processing. This paper took YG20 tungsten steel as the research object, conducted cutting experiments, analyzed the surface morphology characteristics and surface roughness distribution characteristics of the cut surface, and proposed the "inverted reverse secondary cutting" scheme to optimize the surface quality. The results indicated that there is a clear boundary in the

cut surface with ductile fracture area and brittle fracture area. The average surface roughness in the brittle fracture area ($6.725\mu\text{m}$) is significantly larger, about 2.9 times that of the ductile fracture area ($2.314\mu\text{m}$). Increasing the feed rate of the first cutting and using a faster feed rate for the second reverse cutting to polish the cut surface can significantly reduce surface roughness by 27.13-29.17% compared to normal cutting. For YG20 tungsten steel, using 3-4 times the secondary cutting feed rate can achieve the best surface quality. The best polishing effect can be achieved when the secondary cutting feed rate is controlled at 25-32mm/min.

Key word: abrasive suspension jet; liquid nitrogen; tungsten steel; surface roughness.

1. Introduction

Abrasive water jet (AWJ) is a non-contact machining process that is free of heat-affected zones and generates no hazardous waste [1-3]. Based on the different formation methods of solid-liquid mixtures, AWJ is classified into abrasive injection jet (AIJ) and abrasive suspension jet (ASJ). During the formation of ASJ, the water flow is pressurized by a water pump, enters the mixing chamber below the abrasive tank at an extremely high speed, and is thoroughly mixed with the abrasive particles in the tank [4,5]. The solid-liquid mixture is then ejected from the nozzle through a flexible hose. Compared with the entrainment mechanism of AIJ where high-speed water flow draws in abrasive particles, the abrasive particles in the solid-liquid mixture formed by ASJ are more uniformly distributed in the water flow, acquire greater kinetic energy, and exert stronger destructive force on materials [6,7]. Therefore, ASJ exhibits better cutting performance for metals than AIJ and has been widely applied in the cutting of various metals [8,9].

In order to enhance the cutting performance of ASJ for metals, extensive research has been conducted by scholars over the past decade. In terms of jet parameter optimization, relevant theoretical and

experimental studies have been relatively mature. Sasikumar [10] investigated the kerf characteristics of hybrid 7075 aluminum matrix composites machined by AWJ, quantified the contribution of each parameter to the response indicators through analysis of variance (ANOVA), and established a multiple regression model for kerf characteristics. It was found that the feed rate had the largest influence weight on the upper kerf width, while the water jet pressure was the key factor determining the kerf angle and surface machining quality. Akincioglu [11] adopted the Taguchi method combined with grey relational analysis (GRA) to conduct abrasive water jet drilling of aramid fiber reinforced polymer (AFRP) composites, obtained reliable results, and significantly improved the drilling quality of composite materials. Regarding the research on the influencing factors of surface roughness in abrasive water jet machining, Wang [12] studied the surface morphology of Ti-6Al-4V titanium alloy machined by abrasive water jet. It was found that the kerf surface can be divided into four distinct zones: the initial zone, smooth zone, transition zone and rough zone. The abrasive particle size was the only parameter affecting the scratch size, and the use of small-sized abrasives could reduce the surface roughness of the initial zone and smooth zone. Vikas [13] analyzed the influence laws of AWJ machining process parameters on the surface roughness of hardened AISI 440C stainless steel, and found that increasing the jet pressure and reducing the stand-off distance and nozzle feed rate could decrease the surface roughness. In the research on AWJ machining of hard and brittle materials, Liu [14] investigated the effect of vibration assistance on the machining performance of micro ASJ drilling of hard and brittle materials represented by single-crystal 4H-SiC wafers. It was found that this technology could simultaneously improve the material removal rate and surface finish, thus exerting a positive effect on the machining process; moreover, the larger the amplitude, the more significant the improvement effect. Wang [15] studied the action mechanism of vibration assistance in improving the material removal process of ASJ

machining of ultra-hard and brittle materials, and found that the material removal process was dominated by brittle erosion caused by jet particle impact, followed by secondary erosion driven by vortices induced by viscous cross flow. Yuan [16] used confined abrasive jet polishing (CAJP) to machine hard and brittle materials, and found that the material removal process of hard and brittle materials could be divided into three distinct stages: the plastic removal stage, plastic-brittle transition stage and brittle removal stage. Confined abrasive jet polishing could effectively reduce the normal impact load and stabilize the abrasive flow field, thereby reducing surface damage and obtaining high-quality smooth machined surfaces. In terms of changing the physical properties of materials by introducing auxiliary machining, Li [17] conducted static tensile tests and Split Hopkinson Pressure Bar (SHPB) tests on nickel-based alloy Inconel 718 at low temperatures, and found that its strength increased and plasticity decreased at low temperatures. The effect of low-temperature assisted cutting of high-temperature alloys was significantly better than that of traditional cutting methods. Yuvaraj [18] used an optical microscope and a scanning electron microscope equipped with energy dispersive X-ray spectroscopy (SEM-EDS) to study the surfaces of aluminum alloys cut by AWJ and low-temperature assisted AWJ, and found that the cutting performance was improved by adopting the low-temperature assisted cutting method.

Currently, extensive research has been conducted by scholars on jet parameter optimization, influencing factors of surface roughness, machining of hard and brittle materials, and introduction of auxiliary machining methods in AWJ cutting, which has greatly improved the material cutting performance of AWJ.

When processing typical ductile metals, ASJ almost always exhibits pure ductile failure on the surface morphology of the incision, and jet tailing is the main factor increasing surface roughness. By reducing the

feed rate, very high cutting efficiency and surface quality can generally be obtained. Limited by the pressure resistance performance of the abrasive tank, the working pressure of ASJ usually does not exceed 50 MPa [7,9]. For high hardness and strength metals such as tungsten steel, the cutting efficiency of ASJ under standard jet parameters is still poor [19]. At present, liquid nitrogen assisted abrasive suspension jet (LN₂-ASJ) can be used for cutting extremely hard metals, with much higher cutting efficiency than ASJ. The specific method is to first use liquid nitrogen jet to cool down the extremely hard metal and reduce its strength, and then use ASJ for cutting. However, in the machining of extremely hard metals by LN₂-ASJ, the surface quality is unsatisfactory. Surface of shallow kerf depth show ductile failure and deep kerf depth show brittle failure [20]. The surface roughness is unevenly distributed throughout the entire surface and has a high average value, which seriously affects the quality of the workpiece formed by LN₂-ASJ in one processing. In order to solve this problem, this paper took YG20 tungsten steel as the research object, conducted cutting experiments, analyzed the surface morphology characteristics and surface roughness distribution characteristics of the cut surface, and proposed the "inverted reverse secondary cutting" scheme to optimize the surface quality.

2. Cutting experiments of tungsten steel by LN₂-ASJ

The processing process of LN₂-ASJ is shown in Fig. 1. Firstly, cool the tungsten steel sample to a very low temperature using liquid nitrogen jet. Then, transfer the sample to the ASJ processing table. When the temperature of the sample rises to a specific processing temperature, ASJ begins to process the sample [20].

The YG20 tungsten steel specimens used in experiments are all cuboid specimens with dimensions of 100mm × 20mm × 10mm (length × width × height) as shown in Fig. 2. A separate liquid nitrogen jet cooling process is performed before each cutting experiment. To lower the experimental cost and simultaneously

reduce the influence of cooling from the previous cutting experiment on the subsequent one, the cutting spacing of the tungsten steel specimens used in this experiment is all set to 1cm. In Fig. 2, the red lines represent all the proposed jet cutting paths for a single tungsten steel specimen.

The experimental equipment includes the liquid nitrogen jet generation platform (Fig. 3), ASJ cutting platform (Fig. 4) and the OLYMPUS super depth of field microscopeas (Fig. 5). The experimental parameters are shown in Table. 1.

3. Analysis of surface morphology and roughness

Fig. 6 shows the macroscopic morphology of the cut surface of YG20 tungsten steel after LN₂-ASJ cutting. It can be seen that there is a clear boundary in the cut surface. The area with small kerf depth is ductile fracture area with tailing. The area with large kerf depth is brittle fracture area with petal shaped fractures. There are significant differences in the morphology of the two areas, therefore, surface roughness was measured separately. The measurement method for surface roughness is also included in Fig. 6. Three boxes were selected in different areas, and 10 equidistant parallel lines were taken from each box to measure their line roughness Ra . The average roughness of all lines is taken to obtain the surface roughness of that area. The OLYMPUS super depth of field microscope can directly calculate the surface roughness of different areas using this method and output the results. When the feed rate is 5mm/min, the measured surface roughness values are shown in Table 2. From Table. 2, it can be seen that the average surface roughness in the brittle fracture area (6.725 μ m) is significantly larger, about 2.9 times that of the ductile fracture area (2.314 μ m).

Fig. 7 shows the microscopic comparison of the ductile fracture area and brittle fracture area under 60 $\times$ microscope magnification. The ductile fracture area exhibits typical cut surface characteristics of

conventional ductile metal cut by ASJ. Regular jet tailing is formed with the main direction along the jet impact direction and deviating towards the opposite direction of feed. In contrast, there is no obvious jet tail in the brittle fracture area, instead, a "ridge" extends along the feed direction appears, and petal-shaped pits can be seen around the "ridges". It can be seen that the ductile fracture area and brittle fracture area on the YG20 tungsten steel cut surface have distinctly different surface morphology characteristics.

Furthermore, depth-of-field photography was performed on the ductile fracture area and brittle fracture area under 60× magnification. 3D depth models were established to analyze the microscopic undulation changes in the Z-axis direction of different areas on the YG20 tungsten steel cut surface.

Fig. 8 shows the 3D depth model and Z-axis elevation distribution map of the ductile fracture area under 60× microscope magnification. It can be seen that in the ductile fracture area, the cut surface exhibits periodic undulations and is simultaneously distributed with a large number of "peak-shaped" protrusions, with a maximum elevation difference of 94.691μm. The Z-axis elevation distribution presents a bimodal-like distribution, and most of the cut surface elevation is within the range of 500-520μm.

Fig. 9 shows the 3D depth model and Z-axis elevation distribution map of the brittle fracture area under 60× microscope magnification. It can be seen that in the brittle fracture area, the cut surface does not have the periodic undulations similar to those in the ductile fracture area, but rather large "ridges" and pits. Meanwhile, a large number of "hill-shaped" protrusions are distributed on the surface, which is also different from the ductile fracture area. The maximum elevation difference is 463.313μm. The Z-axis elevation is mainly distributed in the range of 465-610μm, with a small amount distributed in the ranges of 610-720.5μm and 257.2-465μm. The maximum Z-axis elevation difference in this observation area of the brittle fracture area is 4.89 times that of the ductile fracture area, which is also the reason why the surface

roughness of brittle fracture area is much greater than that of ductile fracture area.

Fig. 10 shows the microscopic comparison of the ductile fracture area and brittle fracture area under 693× microscope magnification. In the ductile fracture area, material removal mainly relies on the sliding and grinding effects of abrasive particles on the tungsten steel cut surface. Under the field of view of the high-power microscope, the slender scratches on the surface of the ductile fracture area along the jet impact direction and deviating towards the opposite direction of feed can be clearly seen. The scratches caused by abrasives in the brittle fracture area are shorter and oriented along the feed direction. Meanwhile, a "ridge" outline exists in the field of view, which is the brittle incision.

Furthermore, to analyze the microscopic undulation changes in the Z-axis direction of different areas on the YG20 tungsten steel cut surface at a smaller local scale, depth-of-field photography was performed on the ductile fracture area and brittle fracture area under 693× magnification, and 3D depth models were established. Fig. 11 and Fig. 12 show the 3D depth models and Z-axis elevation distribution maps of the ductile fracture area and brittle fracture area under 693× microscope magnification, respectively. Comparing the surface micro-morphologies of the ductile fracture area and brittle fracture area at a smaller scale, it can be found that the surface of the brittle fracture area is actually smoother, with its Z-axis elevation concentrated in the range of 75-92.1μm, which conforms to the characteristics of brittle failure surfaces. The surface of the ductile fracture area has trailing grooves of different depths, and a large number of irregular "peak-shaped" protrusions are distributed in its Z-axis elevation.

4. Optimization of surface quality

4.1 Inverted reverse secondary cutting

The process of ASJ one-time forming processing can be divided into two processes: "cutting" and

"polishing". During the cutting process, the main behavior of ASJ is to remove and penetrate the material. After the material is penetrated, most of the ASJ will be injected into the water channel, and a small portion of the ASJ will polish the cut surface to reduce surface roughness. According to the analysis in the previous text, it can be seen that the area with high surface roughness is located in the brittle fracture area of the large kerf depth, which is difficult to polish by ASJ. On the premise of ensuring that ASJ can cut through material, in order to better utilize the energy of ASJ polishing while keeping the cutting time constant, this paper proposes a scheme of "inverted reverse secondary cutting". During normal processing, the feed rate is v_f . For inverted reverse secondary cutting, the tungsten steel is first cut at a feed rate of v_{f1} , then flipped over so that the brittle fracture area faces upwards, and ASJ is used for another reverse cutting at a feed rate of v_{f2} to ensure that ASJ fully polishes the brittle fracture area during the second cutting. The specific scheme diagram is shown in Fig. 13.

In order to make the processing time of inverted reverse secondary cutting consistent with normal processing, the following conditions need to be met:

$$\frac{W}{v_f} = \frac{W}{v_{f1}} + \frac{W}{v_{f2}} \quad (1)$$

where W is the width of tungsten steel sample.

Compared to the second polishing, the first cutting requires more energy, so v_{f2} needs to be greater than v_{f1} , meeting the following conditions:

$$v_{f2} = nv_{f1}, n > 1 \quad (2)$$

Combine formula (1) and formula (2) to get formula (3):

$$\begin{cases} v_{f1} = \left(1 + \frac{1}{n}\right)v_f \\ v_{f2} = (1+n)v_f \end{cases} \quad (3)$$

From formula (3), it can be seen that both the feed rate for first cutting v_{f1} and the feed rate for secondary reverse cutting v_{f2} are greater than the feed rate for normal machining v_f . The larger the n value, the closer v_{f1} is to v_f , meanwhile, v_{f2} will also be larger, resulting in shorter polishing time.

Through preliminary experiments, it is known that when the normal processing feed rates v_f are 5mm/min, 6mm/min, 7mm/min, and 8mm/min, n can be set to 2, 3, and 4, satisfying the above conditions. Table. 3 shows the distribution of feed rates.

4.2 Optimization results and discussion

The surface roughness distribution of normal processing and inverted reverse secondary cutting is shown in Fig. 14. From Fig. 14, it can be seen that overall, adopting the inverted reverse secondary cutting scheme can significantly reduce the surface roughness of brittle fracture area while slightly increasing the surface roughness of ductile fracture area, thereby reducing the average surface roughness of the cut surface and achieving the goal of improving surface quality. The reason for the slight increase in surface roughness in the ductile fracture area is mainly due to the faster first feed rate and shorter polishing time of the abrasive. Therefore, adopting the "inverted secondary reverse cutting" scheme is significant for optimizing the surface quality of LN₂-ASJ cut tungsten steel. When the normal feed rate v_f is 5mm/min, the optimization effect of $n=4$ is the best, and the average surface roughness decreases from 4.021 μ m to 2.848 μ m, a decrease of 29.17%. When the normal feed rate v_f is 6mm/min, the optimization effect of $n=4$ is the best, and the average surface roughness decreases from 4.045 μ m to 2.897 μ m, a decrease of 28.38%. When the normal feed rate v_f is 7mm/min, the optimization effect of $n=3$ is the best, and the average surface roughness decreases from 4.110 μ m to 2.963 μ m, a decrease of 27.91%. When the normal feed rate v_f is 8mm/min, the optimization effect of $n=3$ is the best, and the average surface roughness decreases from 4.146 μ m to

3.021 μm , a decrease of 27.13%.

Fig. 15 shows the decrease rate of brittle fracture area and average surface roughness under different reverse feed rates. From Fig. 15, it can be seen that for brittle fracture area, when the reverse feed rate is reduced from 40mm/min to 32mm/min, the decrease rate of surface roughness is significantly increased, indicating that the polishing effect is getting better and better. When the reverse feed rate is below 32mm/min, the rate of decrease in surface roughness tends to stabilize, further reducing the reverse feed rate results in low returns. For the average surface roughness, when the reverse feed rate is below 25mm/min, the surface roughness of the brittle fracture area is difficult to decrease. However, due to the severe lack of polishing time during the first cutting, the surface roughness of the ductile fracture area increases, resulting in an increase in the average surface roughness. In summary, controlling the reverse feed rate at 25-32mm/min can achieve the best optimization effect.

As shown in Fig. 16, the macroscopic morphology of the optimized inverted reverse secondary cutting scheme with $v_f=5\text{mm/min}$ and $n=3$ is compared with the normal processing. From Fig. 16, it can be seen that the area where significant changes occur macroscopically is the brittle fracture area of the section. After optimization, the brittle fracture "ridge" (marked by the yellow box in the Fig. 16) becomes less due to the grinding of abrasive in the reverse secondary cutting. Because the highest raised part on its cross-section is preferentially removed by abrasive polishing. Therefore, it is possible to make the brittle failure area smoother and reduce its surface roughness while avoiding the formation of new tails.

5. Conclusion

Through the research, the following conclusions are drawn:

1) When cutting tungsten steel by LN₂-ASJ, different fracture modes will be left at different kerf depths

of the cut surface. There is a clear boundary in the cut surface with ductile fracture area and brittle fracture area. The surface morphology of the ductile fracture area is characterized by jet tailing with the main direction along the jet impact direction and deviating towards the opposite direction of feed. The surface morphology of the brittle fracture area is "ridges" extending along the feed direction, with pits around the ridges and a large number of "hill-shaped" protrusions distributed on the surface. The average surface roughness in the brittle fracture area ($6.725\mu\text{m}$) is significantly larger, about 2.9 times that of the ductile fracture area ($2.314\mu\text{m}$).

2) A scheme of "inverted reverse secondary cutting" was proposed to optimize surface quality. Increasing the feed rate of the first cutting and using a faster feed rate for the second reverse cutting to polish the cut surface can significantly reduce surface roughness by 27.13-29.17% compared to normal cutting. When the normal feed rate is 5mm/min or 6mm/min, using 4 times the secondary cutting feed rate can achieve the best surface quality. When the normal feed rate is 7mm/min or 8mm/min, using 3 times the secondary cutting feed rate can achieve the best surface quality. For YG20 tungsten steel, the best polishing effect can be achieved when the secondary cutting feed rate is controlled at 25-32mm/min.

Declarations

Ethical Approval

Not applicable.

Consent to Participate

Not applicable.

Consent to Publish

All authors agree to transfer copyright of this article to the Publisher.

Authors Contributions

Chiheng Qiang conceived of the study, designed the study and wrote the manuscript. All authors were involved in collecting and analyzing the data, also revisions.

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Competing Interests

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Availability of data and materials

The data sets supporting the results of this article are included within the article and its additional files.

References

1. Natarajan Y, Murugesan PK, Mohan M, Khan SALA (2020) Abrasive water jet machining process: a state of art of review. J Manuf Process 49:271–322. <https://doi.org/10.1016/j.jmapro.2019.11.030>
2. Chen X, Guan J, Deng S, Qiang L, Ming C (2018) Features and mechanism of abrasive water jet cutting of Q345 steel. Heat Technol 36(1):81–87. <https://doi.org/10.18280/ijht.360111>
3. Paola BA, Tarcísio BC (2020) A microscopic study on kerfs in rocks subjected to abrasive waterjet

273 cutting. *Wear* 448–449:203–210. <https://doi.org/10.1016/j.wear.2020.203210>

274 4. Borkowski J, Borkowski P (2009) Criteria of effective materials cutting with suspension abrasive-water
 275 jet. *Arch Civ Mech Eng* 9(2):5–14. [https://doi.org/10.1016/S1644-9665\(12\)60056-9](https://doi.org/10.1016/S1644-9665(12)60056-9)

276 5. Deepak D, Anjaiah D, Karanth KV, Sharma NY (2012) CFD simulation of flow in an abrasive water
 277 suspension jet: the effect of inlet operating pressure and volume fraction on skin friction and exit kinetic
 278 energy. *Adv Mech Eng* 2012:186430. <https://doi.org/10.1155/2012/186430>

279 6. Liu D, Huang CZ, Wang J, Zhu HT (2021) Material removal mechanisms of ceramics turned by abrasive
 280 waterjet (AWJ) using a novel approach. *Ceram Int* 47(11):15165–15172.
 281 <https://doi.org/10.1016/j.ceramint.2021.02.076>

282 7. Ramesha K, Santhosh N, Kiran K, Manjunath N, Naresh H (2019) Effect of the process parameters on
 283 machining of GFRP composites for different conditions of abrasive water suspension jet machining.
 284 *Arab J Sci Eng* 44(9):7933–7943. <https://doi.org/10.1007/s13369-019-03973-w>

285 8. Li ZB, Yao SM, Yun FH, Wang XY, Wang LQ, Wu YT (2022) Simulation and optimization of the nozzle
 286 section geometry for a suspension abrasive water jet. *Machines* 10(1):3.
 287 <https://doi.org/10.3390/machines10010003>

288 9. Kim JG, Song JJ, Han SS, Lee CI (2012) Slotting of concrete and rock using an abrasive suspension
 289 waterjet system. *KSCE J Civ Eng* 16(4):571–578. <https://doi.org/10.1007/s12205-012-1411-1>

290 10. Sasikumar K, Arulshri K, Ponappa K, Uthayakumar M (2018) A study on kerf characteristics of hybrid
 291 aluminium 7075 metal matrix composites machined using abrasive water jet machining technology. *P*
 292 *I Mech Eng B-J Eng* 232(4): 690-704. <https://doi.org/10.1177/0954405416654085>

293 11. Akincioglu S (2021) Investigation of effect of abrasive water jet (AWJ) machining parameters on

294 aramid fiber-reinforced polymer (AFRP) composite materials. *Aircr Eng Aerosp Tec* 93(4):615–628.

295 <https://doi.org/10.1108/AEAT-11-2020-0249>

296 12. Wang F, Yang K, Xiao N, Li L, Guo C (2021) Quantitative analysis on the surface topography of ti-

297 6Al-4V machined by abrasive suspension jet. *Int J Adv Manuf Tech* 2021;112(1-2):323-332.

298 <https://doi.org/10.1007/s00170-020-06373-9>.

299 13. Sisodia V, Gupta SK, Salunkhe S, Murali AP, Kumar S. (2024) An experimental investigation on

300 machining of hardened AISI 440C stainless steel using abrasive water jet machining process. *J Mater*

301 *Eng Perform* 2024;33(2):961-977. <https://doi.org/10.1007/s11665-023-08040-y>.

302 14. Liu D, Nguyen T, Wang J, Huang C (2020). Mechanisms of enhancing the machining performance in

303 micro abrasive waterjet drilling of hard and brittle materials by vibration assistance. *Int J Mach Tool*

304 *Manu* 151: 103528. <https://doi.org/10.1016/j.ijmachtools.2020.103528>

305 15. Wang J, Nguyen T (2021). Mechanisms and predictive models for the erosion process of super hard and

306 brittle materials by a vibration-assisted slurry jet. *Int J Mech Sci* 211: 106794.

307 <https://doi.org/10.1016/j.ijmecsci.2021.106794>

308 16. Yuan Q, Ye X, Wen D, Chen Z (2025). Subsurface damage of constrained abrasive jet polishing based

309 on SPH method. *Int J Adv Manuf Tech* 141(9): 5709-5719. [https://doi.org/10.1007/s00170-025-16911-](https://doi.org/10.1007/s00170-025-16911-y)

310 [y](https://doi.org/10.1007/s00170-025-16911-y)

311 17. Huang ZW, Wu XG, Li R, Zhang SK, Yang RY (2019) Mechanism of High Pressure Liquid Nitrogen

312 Jet to Improve Drilling Speed in Deep Wells. *Petrol Explor Dev* 46(4):768-775 (in Chinese with

313 English abstract). <https://doi.org/10.11698/PED.2019.04.16>

314 18. Natarajan Y, Murugasen PK, Sundarajan LR, Arunachalam R. (2019) Experimental investigation on

cryogenic assisted abrasive water jet machining of aluminium alloy. *Int J Pr Eng Man-GT* 2019:1-18.

<https://doi.org/10.1007/s40684-019-00072-x>

19. Krenicky T, Servatka M, Gaspar S, Mascenik J (2020) Abrasive water jet cutting of Hardox steels-

quality investigation. *Processes* 8(12):1652. <https://doi.org/10.3390/pr8121652>

20. Qiang CH, Teng WX, Fei SH, Guo CW, Shen G (2025) Effect of initial temperature on cutting speed in

liquid nitrogen-assisted abrasive suspension jet machining of tungsten steel. *Int J Adv Manuf Tech*

137(3):1235-1247. <https://doi.org/10.1007/s00170-025-15263-x>.

Figures and Tables Captions

Fig.1. Machining process of LN₂-ASJ

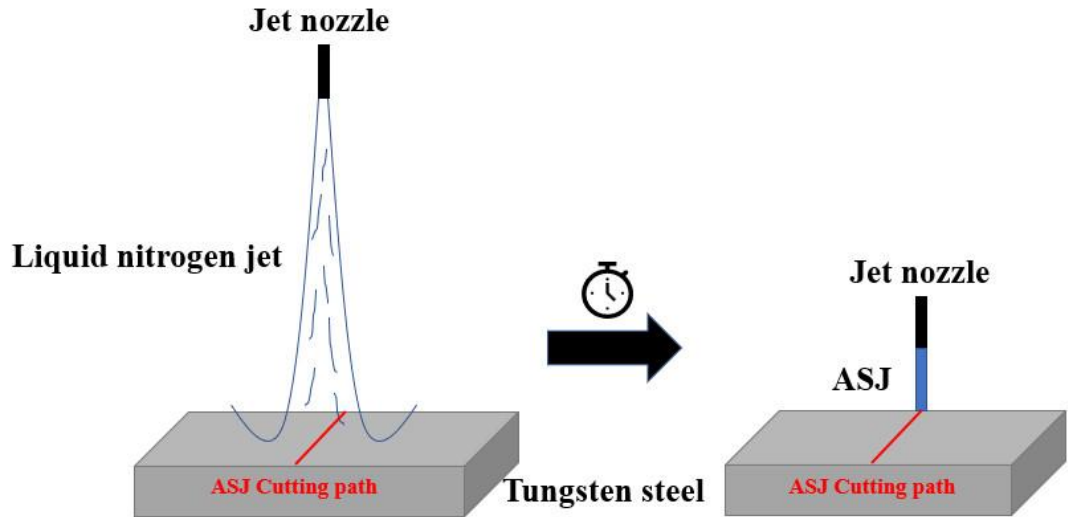


Fig. 2. YG20 tungsten steel sample

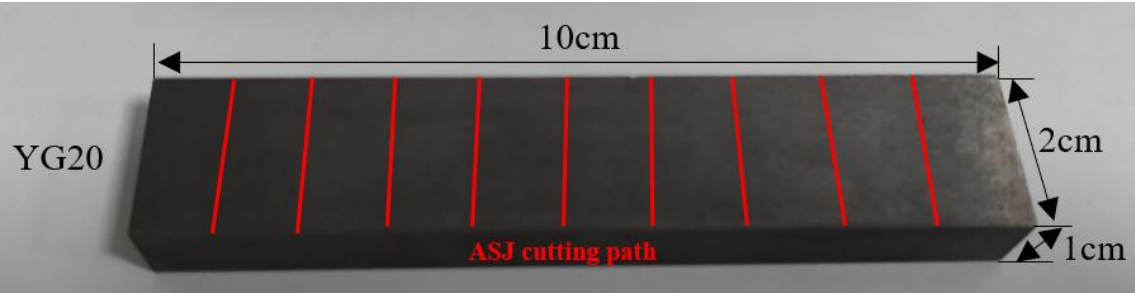


Fig. 3. Liquid nitrogen jet generation platform

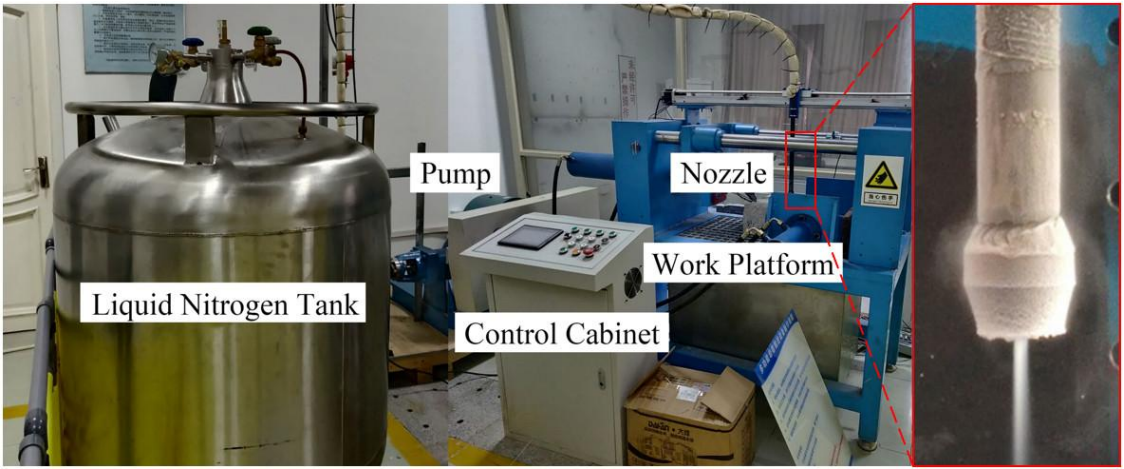


Fig. 4. ASJ cutting platform

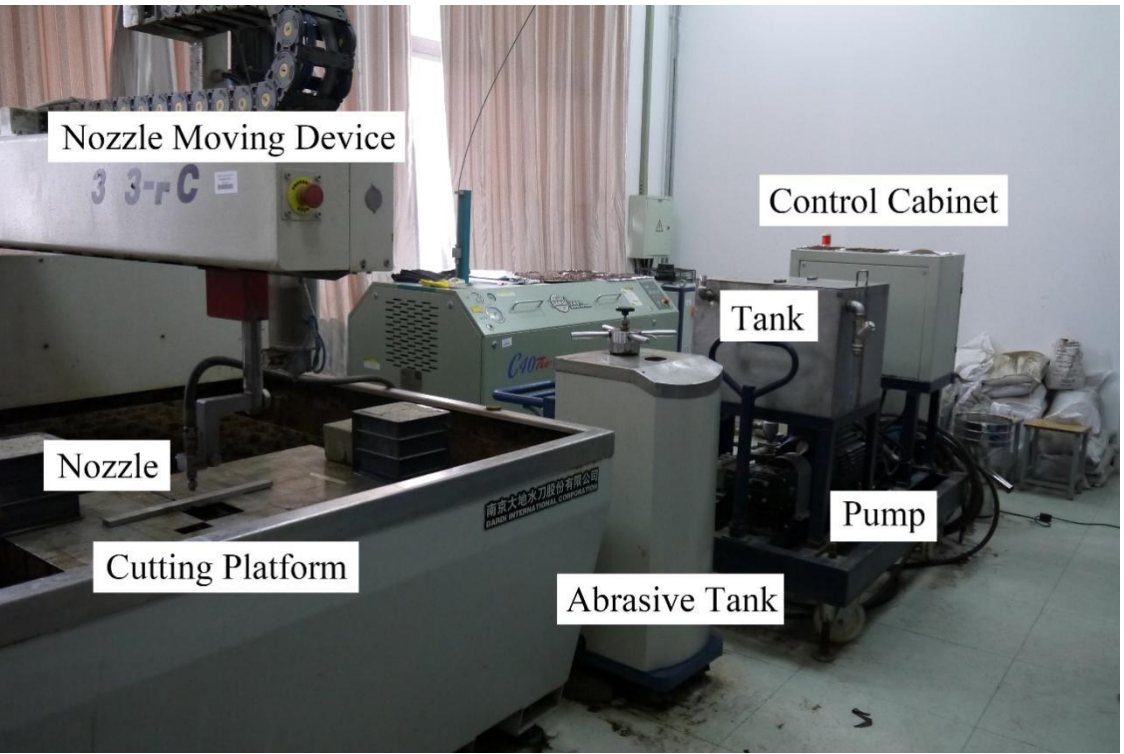


Fig. 5. OLYMPUS super depth of field microscopeas

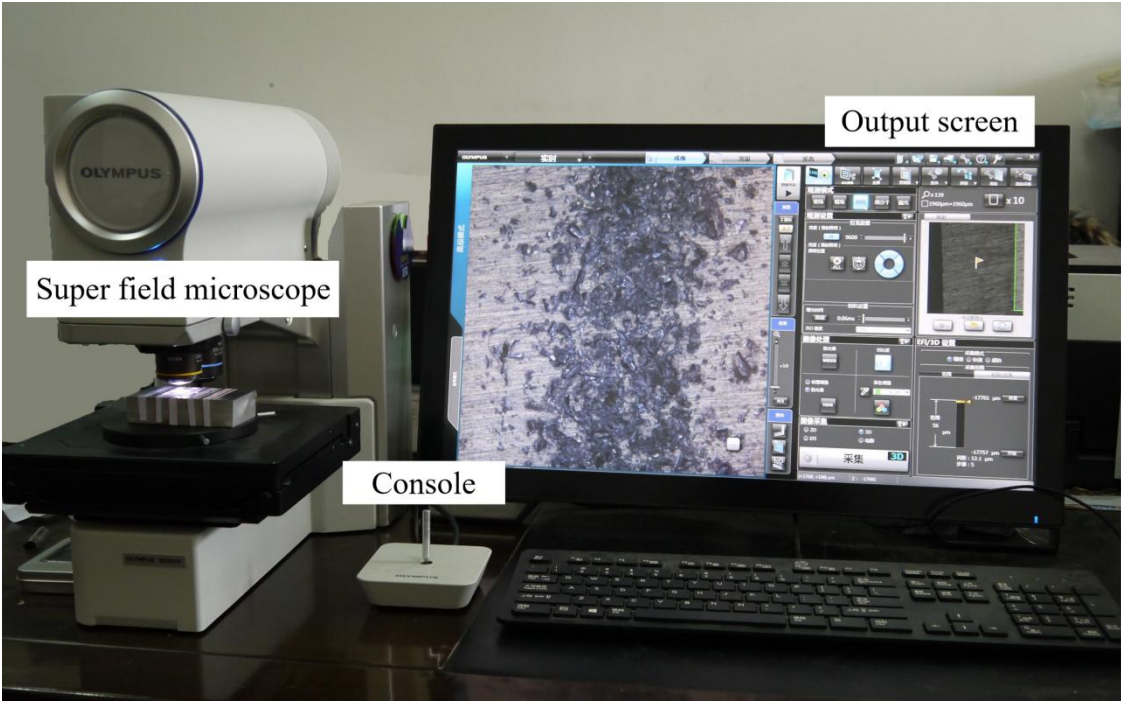


Fig.6. Macroscopic morphology of the cut surface of YG20 tungsten steel after LN₂-ASJ cutting

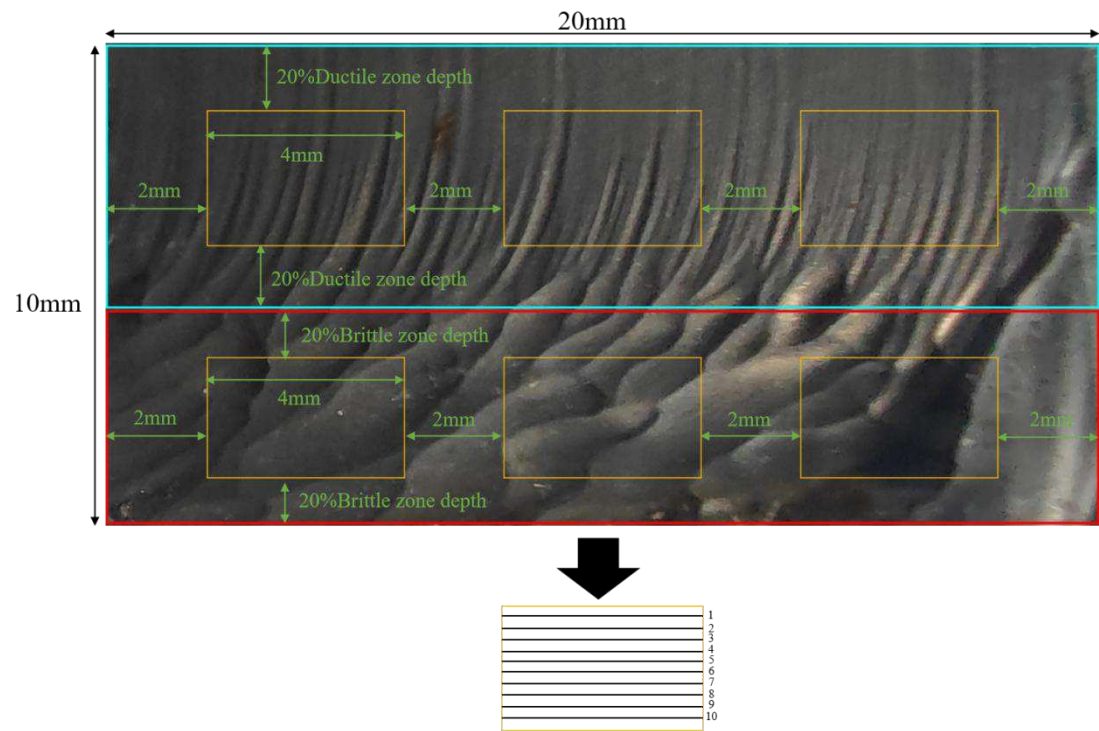


Fig. 7. Microscopic comparison of ductile fracture area and brittle fracture area under 60× microscope magnification

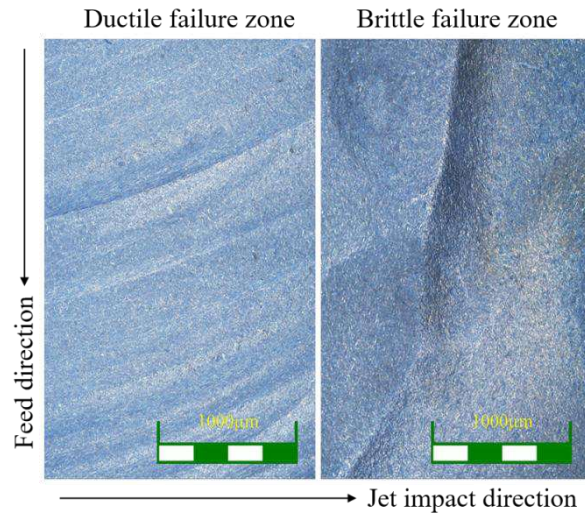


Fig. 8. 3D depth model and Z-axis elevation distribution map of ductile fracture area under 60× microscope magnification

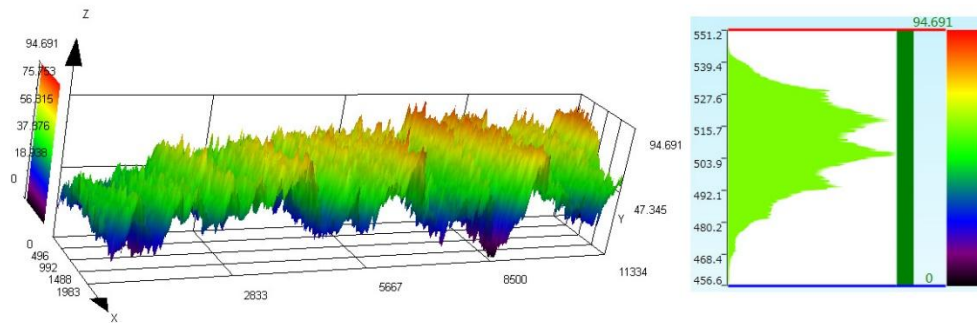


Fig. 9. 3D depth model and Z-axis elevation distribution map of brittle fracture area under 60× microscope magnification

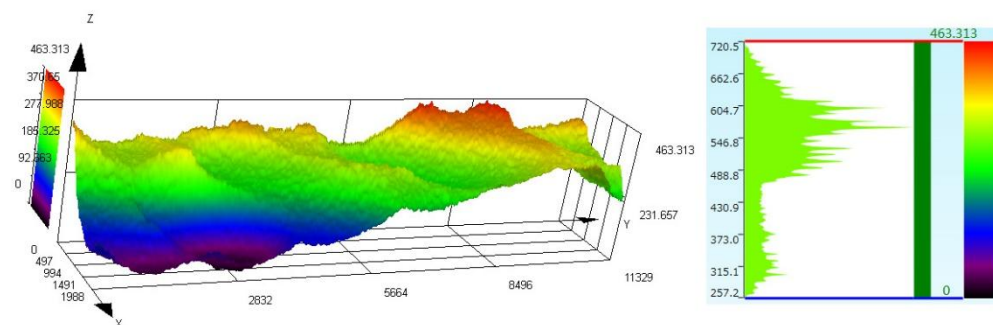


Fig. 10. Microscopic comparison of ductile fracture area and brittle fracture area under 693× microscope magnification

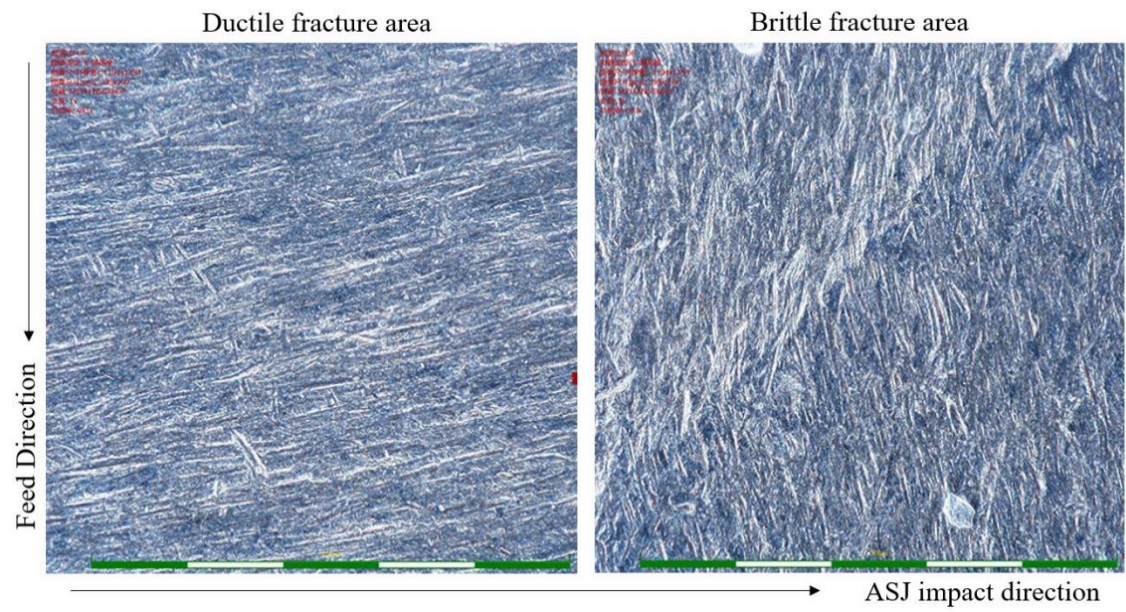


Fig. 11. 3D depth model and Z-axis elevation distribution map of ductile fracture area under 693× microscope magnification

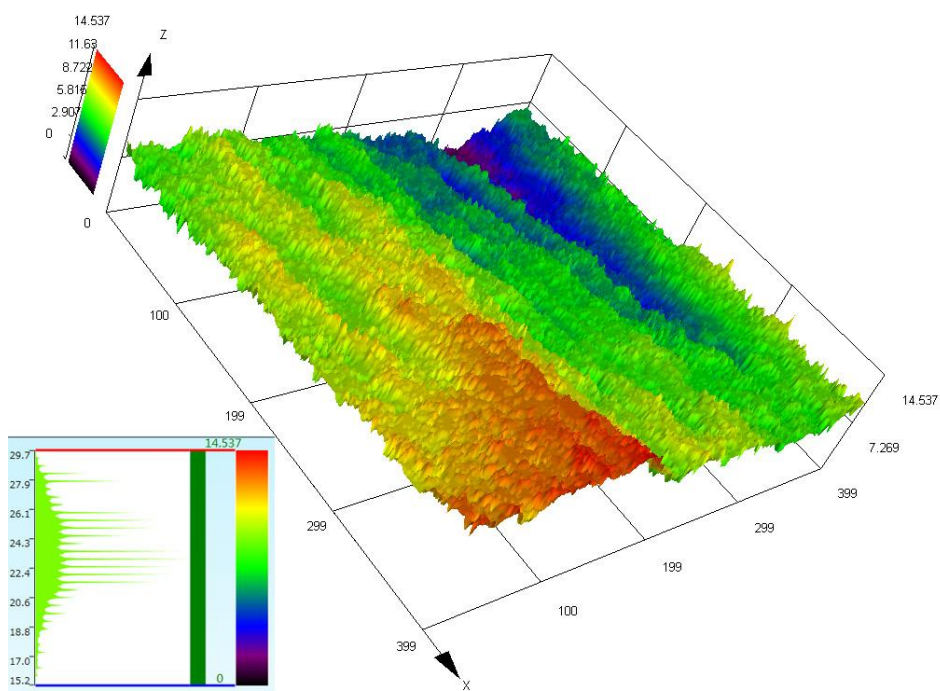


Fig. 12. 3D depth model and Z-axis elevation distribution map of brittle fracture area under 693× microscope magnification

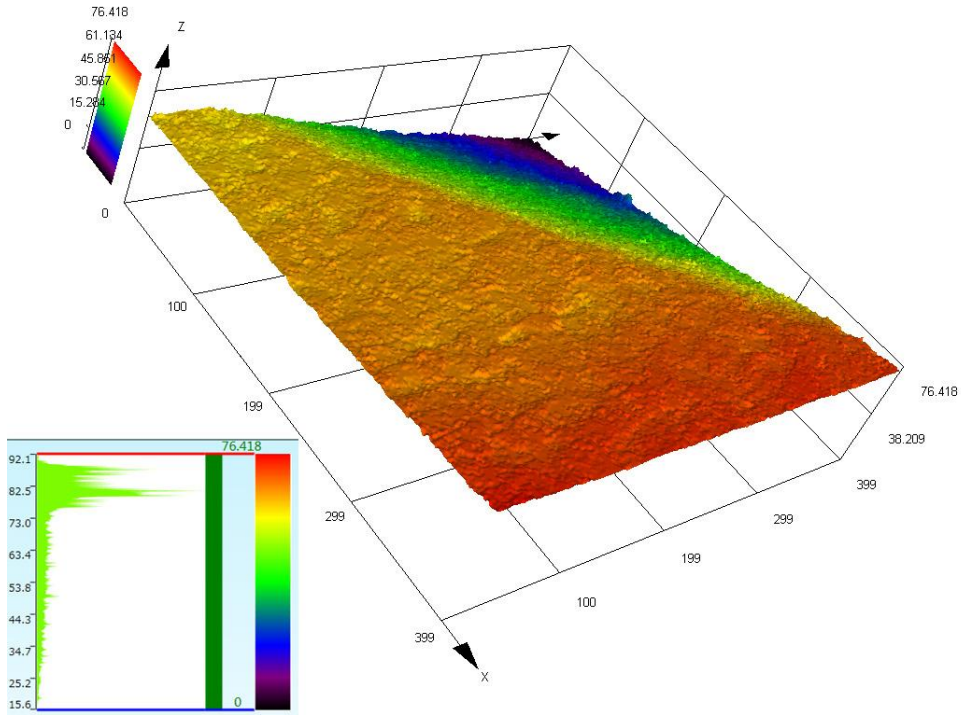


Fig. 13. Scheme of "inverted reverse secondary cutting"

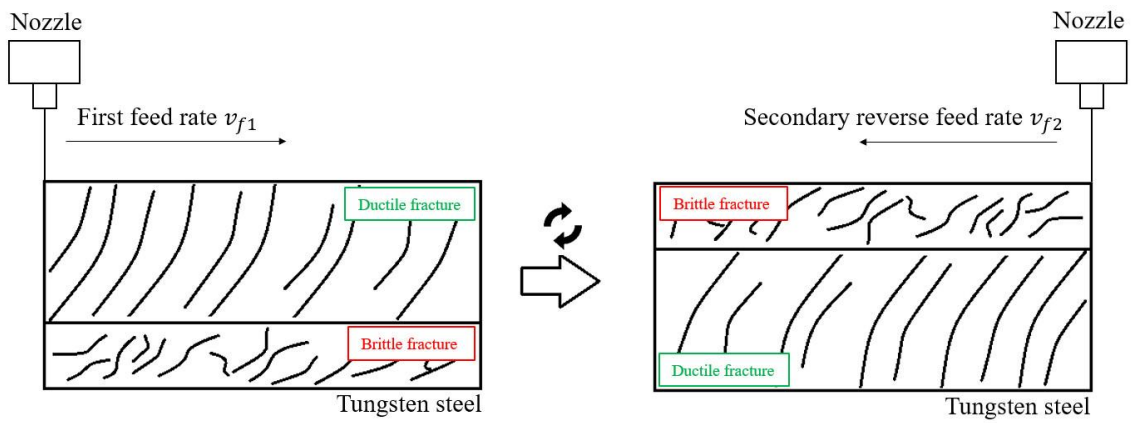


Fig. 14. The surface roughness distribution of normal processing and inverted reverse secondary cutting

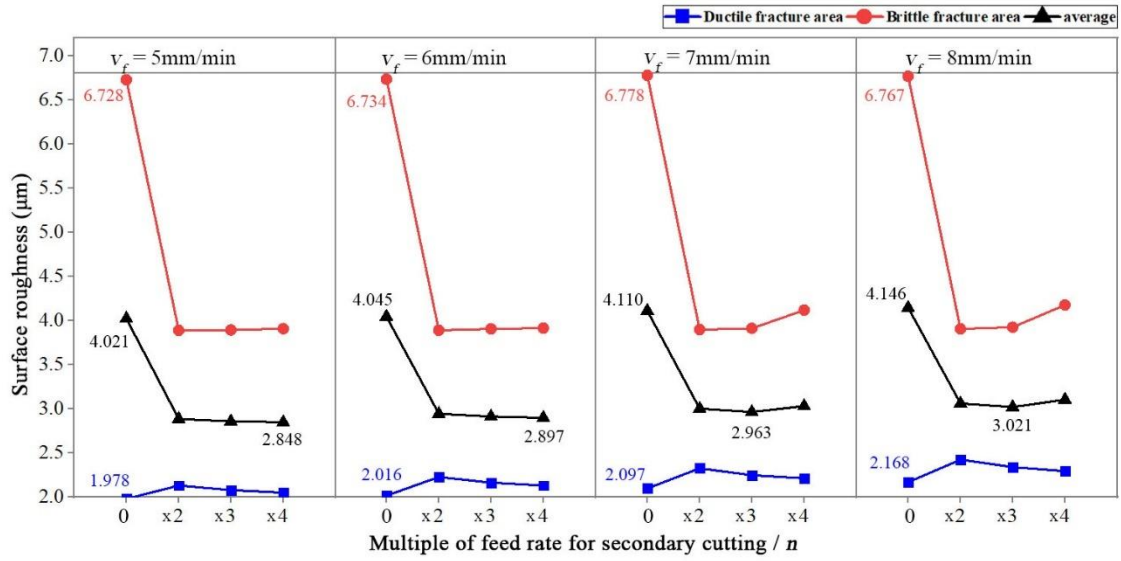


Fig. 15. The decrease rate of brittle fracture area and average surface roughness under different reverse feed

rates

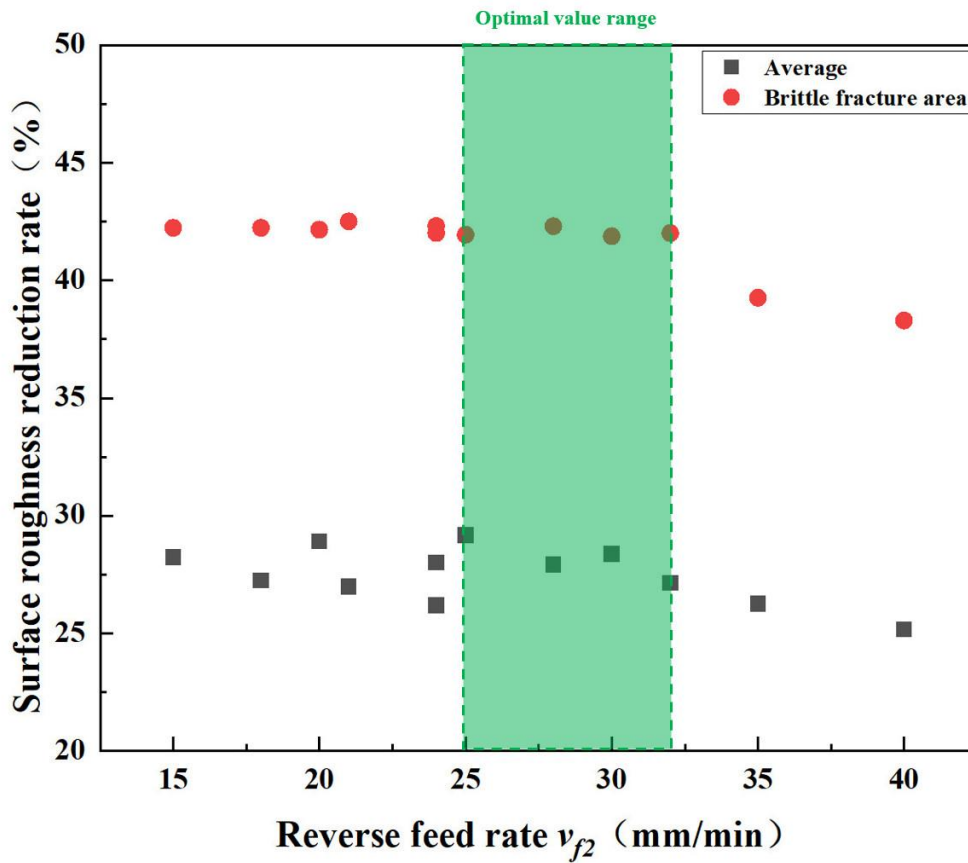


Fig. 16. Optimization results of inverted reverse secondary cutting with $v_f=5\text{mm/min}$ and $n=3$

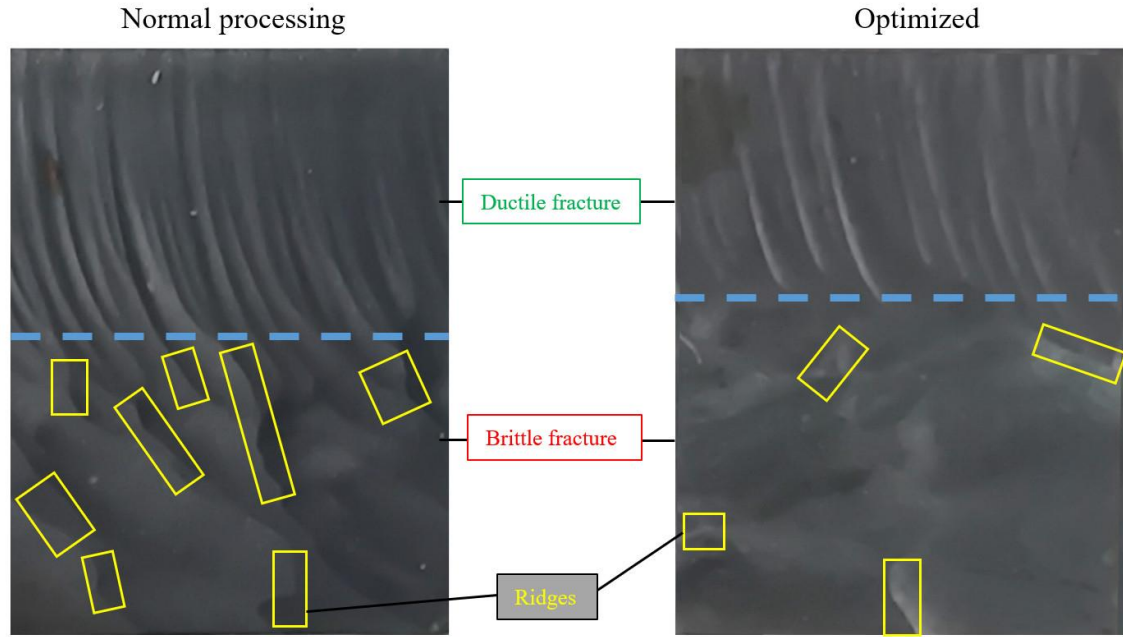


Table. 1. Experimental parameters

Parameters	Values
Temperature of liquid nitrogen (°C)	-196
Processing temperature (°C)	-80
Abrasive type	80 mesh SiC
Stand-off distance (mm)	3
Pressure of ASJ (MPa)	40
Traverse rate (mm/min)	5, 6, 7, 8
ASJ nozzle diameter (mm)	1

403 Table. 2. The measured surface roughness values when the feed rate is 5mm/min

No.	Ra of ductile fracture area (μm)	Ra of brittle fracture area (μm)	Average surface roughness (μm)
Box 1	2.467	6.472	/
Box 2	2.325	6.631	/
Box 3	2.150	7.072	/
Average	2.314	6.725	4.378

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405 Table. 3. The distribution of feed rates

Multiple of feed rate for secondary cutting / n	First feed rate v_{f1} (mm/min)	Secondary reverse feed rate v_{f2} (mm/min)
0 (normal processing)	5	/
	6	/
	7	/
	8	/
2	7.5	15
	9	18
	10.5	21
	12	24
3	6.7	20
	8	24

	9.3	28
	10.7	32
	6.25	25
	7.5	30
4	8.75	35
	10	40

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