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ORIGINAL ARTICLE

Green machining of aluminum honeycomb treated using ice fixation in cryogenic

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Abstract This paper aimed to restrain the processing defects of aluminum alloy honeycombs using in aerospace with low stiffness and thin-walled, such as burr and collapse edge. The honeycomb material was treated by new method named ice fixation, and a CNC milling machine was used for a series of cryogenic machining. The fixation strength was calculated and machining defect reasons were analyzed. The cryogenic milling mechanism with ice fixation was established at the same time. Results show that compared to the without ice or conventional fixation way, the honeycomb fixation force and strength are all greatly increasing and that can reach 287 N and 19.1 kPa, respectively. Meanwhile, the processing defects are effectively suppressed. Others the cutting depth has greater influence on surface quality, and it makes the milling force improved three times, while the improvement of fixation and milling force and the cryogenic processing are the main reasons of reducing defects. The ice fixation cryogenic processing provides a new and effective method for aluminum alloy honeycomb with low rigidity and thin-wall.

Keywords Aluminum alloy honeycomb · Low stiffness · Processing defects · Fixation strength · Cryogenic milling · Cutting parameters

1 Introduction

The mental alloy honeycombs especially the aluminum ones all have light weight, high strength, good rigidity, long service life, outstanding comprehensive functions, high appearance straightness, not easily deformation, good processing adaptability features, and so on [1, 2]. They are widely utilized in aerospace, aviation, shipbuilding, and other important fields [3, 4]. For aerospace workpieces with complicated shape, such as rocket fairing, rudder, spacecraft landing gear, and doors, the metal honeycomb must be processed into all kinds of complicated shape structure [4, 5]. As the investigation results about the thin-wall porous structure, the thickness is generally less than 0.1 mm, and length of perforation generally is less than 10 mm. This structure makes honeycomb have high strength along the perforated axial, but the in-plane equivalent strength in radial is much poor. After sustaining radial force, it will inevitably have a certain deformation. So, under the action of mechanical processing, the fixation and clamping method of conventional cannot be adopted [5].

Usually in honeycomb machining, especially for aerospace materials, metal honeycomb workpieces need to accurate positioning and clamping. Due to low rigidity thin wall, the materials are easy to deform using the conventional fixation clamp way. It will lead to lower manufacturing precision and only about 30% efficiency, while it will make the processing cost as high as 90% [6]. So some of them cannot satisfy the assembly requirements of aviation and will affect the practical function of the products [7, 8].

At present, the advanced honeycomb fixation methods are electromagnetic [9, 10] and vacuum adsorption methods [11]. For the electromagnetic adsorption, if honeycomb is filled with iron filings, the filler metal will be inevitable cut at the same time, which will cause the iron splash, cutting force and cutting temperature increased. But if it is not full, the machining vibration is also inescapable, so the machining accuracy will be affected, especially for the poor stiffness honeycomb. And for the complicated shape structure honeycomb workpiece using in aerospace, the fixation process cannot be quite qualified. As well as the electromagnetic fixation equipment is complex, and the change

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of the magnetic field cannot be accurate controlled. In addition, cleaning of iron filing is also a complex work. Others for the vacuum adsorption method, due to the insufficient adsorption force for the whole workpiece, the machining accuracy will be also impacted. In addition, the structure of adsorption device and the workpiece clamping ways are complex and need long work time, and the vacuum degree is difficult to be maintained for long time machining work. So this method is difficult for the clamping fixation reliability in long time and the efficiency of clamping. Besides, the wax or polyethylene was poured into the honeycomb to strengthen the fixation ability and improve processing qualities [12, 13]. Through it can obtain sufficient fixation strength, much time and labor were spent to wax, mill, and clean. Especially, the residual filled materials and produced gas seriously polluted environment. It was also found that using wax process obviously increased production cost.

At the same time, honeycomb processing technology mainly include carborundum tool cutting, laser cutting technology, and high-speed CNC machining, especially complexity honeycomb materials usually employ five axis high-speed milling machining with special milling tool [14, 15]. Wang [16] designed the special milling tool and optimized the tool structure size according to the results of the experiment. Finally, the better cutting effect was obtained. But because of the effect of cutting force and cutting heat, in high speed machining, the alloy in cutting zone appeared adhesion phenomenon and that caused tool surface rapid failure.

Others, because aluminum alloys have many advantage properties in the cryogenic applications, such as high strength and strength to gravity ratio, and high yield strength are very favorable for high efficiency machining. Meanwhile, some of the present authors previously also reported different properties, such as the tensile properties, fracture toughness, and high cycle fatigue for the alloys in cryogenic [17–19].

Based the completely fixation method such as the wax or polyethylene [12, 13], and abandoned their defects, in this paper, the high-speed green milling methods in cryogenic with ice fixation are used to deal with low rigidity alloy honeycomb. The ice is acted as a fixation medium to improve fixation force like the wax but no pollution, and liquid nitrogen is employed as cryogenic medium to realize cryogenic processing and maintain fixation state. Under the condition of high speed milling, the method and performances of ice fixation are researched, as well as the effects of cutting parameters on milling performance.

2 Experimental details

2.1 Honeycomb ice fixation strength test

1. Ice performance test

Along with the processing at room temperature, ice temperature is rising and the melting is inevitable, which will influence ice fixation strength, so that ought to test and analyze the ice properties. Here, the ultimate compressive strength, Moh s hardness and compressive strength of ice were considered.

a. The CSS-44100 type electronic testing machine and low temperature chamber were employed to test ultimate compressive strength. The access precision of the chamber reached 0.1 °C, and the equipment could implement secondary temperature control, its resolution ratio is 0.01 °C. The test temperatures were −5, −10, −15, −20, −25, −30, and −35 °C. Others the strain rate was 10^{-3}/s.

b. Using type M211WF Moh s hardness pen with 1–10 levels estimated the ice hardness in different temperature.
c. Adopting the pressure testing machine of SHS2-3 electric hydraulic type and the cryogenic temperature test chamber of Haier DW-50W255 type measured the ice compressive strength. The ice wordpieces were maintained a constant temperature more than 24 h. Considering vertical milling in this paper, loading direction was horizontal. The ice temperatures were −5, −10, −15, −20, −25, −30, −35, and −40 °C. At last, the strain rate of 10^{-3}/s was also chosen.

2. Honeycomb ice fixation strength test scheme

Based on the theory of mechanics and cutting, the fixation strength could be measured by the following:

a. The fixation platform was shown in Fig. 1. At first, the honeycomb was located in the fixture, and water was filled with higher 2 mm than its top. Then, the fixture with honeycomb was put in the cryogenic temperature test chamber and frozen more than 24 h (Fig. 1a). Lastly, the metal outer wall of fixture was quickly removed, and the side and top surfaces of ice were leaved which was shown in Fig. 1b.
b. As illuminated in Fig. 1b, the local coordinate system can be established. According to the system, the fixation properties consisted of fixation strengths in x, y, and z directions, respectively. They were τ_{zx}, τ_{zy}, and τ_z, and in horizontal it was $\tau_{zx} = \tau_{zy}$.

3. Fixation strength calculation

a. The fixation honeycomb specimen was loaded tension force in z direction. The loaded force was from small to large, until the honeycomb was loose and come off from the platform; at this moment, the forces were by recorded and named F_z. The fixation function in z direction was attributed to the static friction force between the ice and honeycomb wall. In machining process, the friction force

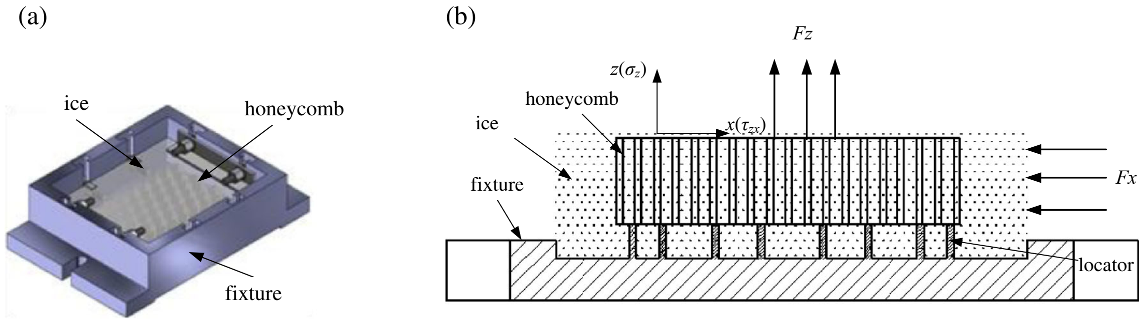

Fig. 1 Ice fixation platform. **a** Ice fixation fixture. **b** Fixation strength

and F_z reached balance and prevented honeycomb movement in this direction. Therefore, the fixation strength could be expressed by the formula (1).

$$\tau_z = \frac{F_z}{\sum_{i=1}^{n} S_{zi}} \quad (1)$$

where i was the honeycomb number and $\sum_{i=1}^{n} S_{zi}$ was the total contact area between ice and honeycomb wall.

b. In the horizontal subjected to x or y direction force, the honeycomb had the trend of relative movement with the platform. There were static friction force between the honeycomb and ice with platform, and the direction was parallel to the platform surface. At this time, the honeycomb and ice could be as a whole and had transverse relative motion trend. So, the fixation strength in the two directions could be expressed by the formulas (2) and (3).

$$\tau_{zx} = \frac{F_x}{S_{xy}} \quad (2)$$

$$\tau_{zy} = \frac{F_y}{S_{xy}} \quad (3)$$

where F_x and F_y were the acting force, and S_{xy} was the total contact area between ice and honeycomb wall with platform.

2.2 Machining experiment

1. Experiment material

Aluminum alloys had good fatigue resistance, radiation resistance, oxidation resistance, and corrosion resistance performance. They could also be manufactured to kinds of complex shape parts. So in the aerospace, nuclear power and petroleum industry, the alloys had the extremely widespread application [18], such as rocket and missile, especially for aircraft and rocket engine. One of the aluminum alloys, the 7075 alloy, had been widely employed in cryogenic temperature conditions [19, 20], and the honeycomb components processed were the key and irreplaceable parts in aircraft protection system, and it could be reused.

In this experiment, the aluminum alloy (7075) honeycomb for aerospace was cut into 80 mm × 60 mm × 30 mm cuboid blocks with two adjacent vertical sides who were used as the locating surfaces.

2. Experiment equipment

a. Milling tests were performed on a DMU700 vertical milling machining center equipped with Heidenhain CNC system. The maximum spindle speed of the machining center was 24,000 rpm and the table travel was 300 mm × 300 mm × 200 mm.
b. A kentanium inner-cooling tool with four blades (kyocera, Japanese) was used, and tool diameter was 14 mm. A homemade shank device with inner cooling was adopted to clamp which was shown in Fig. 2a. A pressurized liquid nitrogen tank (Tianhai DPL - 175, Beijing) was employed to provide liquid nitrogen and temperature of the nozzle was controlled at −196 °C. To one pipeline, the liquid nitrogen could be sprayed on the cutting point through the pores at the end of the tool. To another, the liquid nitrogen was sprayed onto the ice to keep in low temperature.
c. The ice temperature was obtained by the chamber (DW-50W255, Haier) whose adjustment scope of temperature could be adjusted from −20 to −90 °C.

3. Manufacturing methods

On the principle, the ice fixation method was similar with perfusion wax or magnet powder, but that had advantage on the way of cleanliness than the latters. The ready work was similar with the fixation strength test scheme. In detail, before processing, the workpiece was flatted into the fixation fixture. After positioning was completed through the locating surfaces, the distilled water was poured to the fixture. After that,

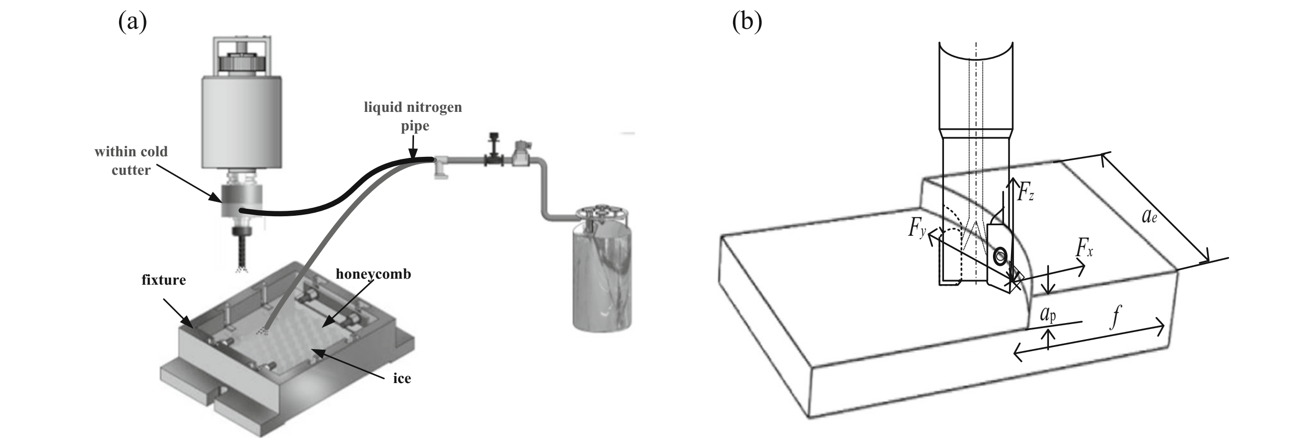

Fig. 2 Cryogenic test platform. **a** Test platform. **b** Machining model

the water just suitably covered on the workpiece surface, and then, it was put in the temperature test chamber for a specific time. Furthermore, the fixture with workpiece was removed from the temperature test chamber, and it was quickly clamped on the workbench of the machining center.

Based on the frequent testing experience in ice fixation cryogenic test, the main experiment parameters were shown in Table 1 in detail. Besides, the milling constant width was 6 mm. In detail, for different cutting depths, the feed speed and spindle speed were 150 mm/min and 8000 rpm. Meanwhile, for different feed speeds, the other two parameters were 1 mm and 8000 rpm, and for spindle speeds, the other values could be gotten from the former ones.

Table 1 Experiment parameters

No.		Cutting depth/mm	Feed speed/ (mm/min)	Spindle speed *n*/rpm	Temperature/ °C
Cutting depth	1	0.5	150	8000	−50
	2	1	150	8000	−50
	3	1.5	150	8000	−50
	4	2	150	8000	−50
	5	2.5	150	8000	−50
	6	3	150	8000	−50
Feed speed	7	1	50	8000	−50
	8	1	100	8000	−50
	9	1	150	8000	−50
	10	1	200	8000	−50
	11	1	250	8000	−50
	12	1	300	8000	−50
Spindle speed	13	1	150	500	−50
	14	1	150	1000	−50
	15	1	150	2000	−50
	16	1	150	4000	−50
	17	1	150	8000	−50
	18	1	150	11,000	−50

The decomposition model of milling force was shown in Fig. 2b; in three intersection directions, there were feed force F_x, vertical force F_y, and back force F_z. In this paper because of the main contribution to the cutting, only the vertical force F_y was researched and was named the main milling force. Others the a_p and a_e were the cutting depth and the cutting width, and f was for the feed.

4. Analysis equipment

The SLR cameras (Nikon D7100, Japan) with focal length 16~85 mm was engaged to obtain machining scenery. The morphology and structure of the surfaces were analyzed by FEI-SIRION scanning electron microscope (SEM).The workpiece surface morphologies were measured by an ultra-deep microscope digital microscope (KEYENCE VHX- 600, Japan) with resolution of 54 million pixels. The surface roughness was tested by a 3D surface contourgraph (ZYGO New view5022, USA) with the vertical resolution of 0.1 nm and measurement of 0.001 μm. And the cutting forces of cutting point were acquired by a three-phase dynamometer (Kisler9257B, Swiss). The phase composition surfaces were conducted by X-ray diffraction (XRD) whose type was D/max-rB and made in RIGAKU Corporation.

3 Results and discussion

3.1 Ice fixation experimental results

1. Ice properties

The experimental results of ice properties are shown in Fig. 3. With decrease of ice temperature, the ultimate compressive strength is increase, but at −25 °C, the increasing trend is slowing down. The Moh s hardness has also the same trend, and after −50 °C, the value is stability in 5. At last for the compressive strength, it can obtain the highest and steady

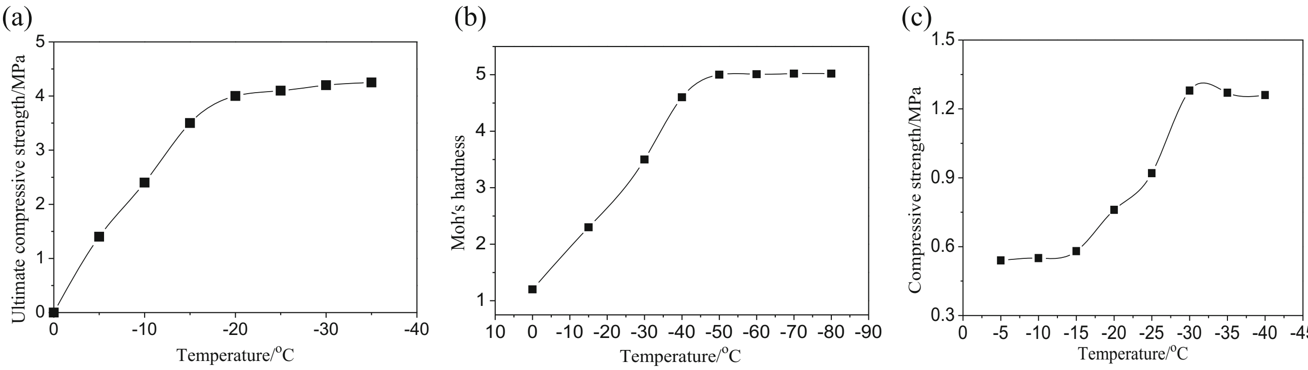

Fig. 3 Ice properties. **a** Ultimate compressive strength. **b** Moh s hardness. **c** Compressive strength

value more than −30 °C. But with increase of temperature, especially more than −25°C, these properties will all be rapidly decreased, which causes a decline of fixation strength and ability. Due to ice had the best performance at −50 °C, in order to achieve the best effect of ice fixation, it should maintain the ice temperature under −50 °C, and the temperature test chamber sets to the level.

2. Measurement results

Based on the foregoing scheme, ice fixation strength measurement results are obtained as illuminated in Table 2 with the values of electromagnetic and vacuum adsorption methods [9–11]. The fixation force and strength have obviously increased than other methods. Especially there are about two times bigger than the vacuum adsorption and 30% higher than the electromagnetic method. So, the fixation ability is better than the electromagnetic and vacuum adsorption methods.

3.2 Surface morphology

The machine scenery of honeycomb is shown in Fig. 4.The homemade fixture can contain the ice and locate the honeycomb (Fig. 4a). Meanwhile, after working 5 min, there is no frost phenomenon for the liquid nitrogen pipeline (Fig. 4b). In cryogenic condition, after long time processing, the ice still keeps the frozen state and has stable fixation force (Fig. 4c), as well as the processing morphology of honeycomb with or without ice fixation was depicted in Fig. 5. For without ice fixation, the processed surface has burr, curl, and collapse, especially for serious deformation which is bigger on the edge of the workpiece (Fig. 5a, b). It can be revealed that the honeycomb has small radial equivalent strength in-plane, and stiffness is insufficient. So after processing, the curl deformation and collapse edge are easy left. Furthermore, the alloy has strong plasticity, it makes chip not easily broken.

At the same time, in processing, the internal stress is also easy to make brazing surface open welding at honeycomb connection place. These defects lead to honeycomb performance failure. On the contrary, ice fixation processing surface is smooth and level who can be derived by Fig. 5c. The relevant defects are well suppressed. And with the increase of spindle speed especially at high speed, the surface quality is better as illustrated in Fig. 5d–f. There are almost no burr or curling defects, especially the deformation. The whole workpieces are all qualified than the conventional processes.

Considering the honeycomb surface quality with no ice, it is too worse to estimate, so the analysis is only for the ice fixation one. As illustrated in Fig. 6a, with the increase of speed, the value of surface roughness is obviously decreasing in ice fixation cryogenic processing conditions, and then it tends to flatten out and stable at high speed. The surfaces are more smooth even reaching Ra = 0.38 μm. Similarly, with cutting depth increases, the roughness value is increased significantly after cutting depth of 1.5 mm in details, and that has bigger effect on surface quality than the speed, especially in bigger cutting depth, as shown in Fig. 6b, and the value can reach Ra = 2.0 μm.

Table 2 Fixation force of three types

	F_x (N)	F_y (N)	F_z (N)	τ_{zx} (kPa)	τ_{zy} (kPa)	τ_z (kPa)
Vacuum adsorption	98	98	42			
Electromagnetic	216	216	150	14.4	14.4	3.25
Ice fixation	287	287	245	19.1	19.1	5.3

3.3 Milling force

3.3.1 Experimental results

At different spindle speed, feed speed and cutting depth, the main milling force, back force, and feed force with and without ice fixation cryogenic are shown in Figs. 7, 8, and 9. It is noticed that the former almost is obviously bigger than the latter. It owes to the increased cutting resistance by ice fixation cryogenic. With the increase of spindle speed, the horizontal forces F_x, F_y are all decreasing as illustrated Fig. 7a, b, and it is worth highlighting that in no ice fixation, the back force of F_z

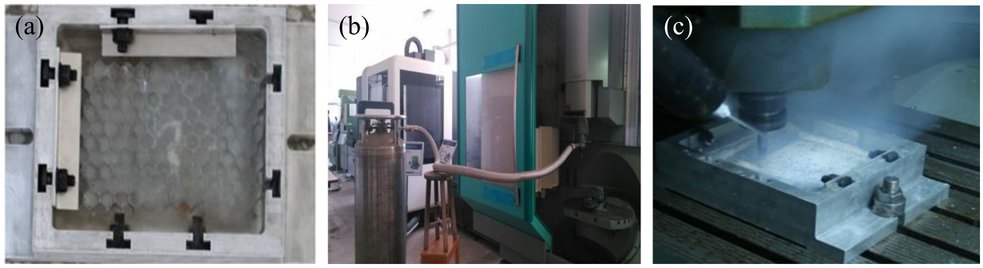

Fig. 4 Machine scenery. **a** Ice fixture. **b** Test platform. **c** Processing in low temperature

little increases in higher speed (Fig. 7c), and it is about 0.2 N bigger in details. It indicates that in the high speed milling oscillations and temperature rise the inflation of cutter and workpiece, which inevitable leads to the axial resistance enhancement.

With the increase of feed speed, the milling force changes little, as shown in Fig. 8. It is obvious that the main cutting force is only enhanced from 5.6 to 9 N for without ice fixation and from 24 to 31 N for ice fixation cryogenic. So the increasing degree is unconspicuous, and the effect of feed speed on cutting force is very small. And for cutting depth, as shown in Fig. 9, the force exhibits a trend of increase, and the change is more obvious, especially at large cutting depth it has the bigger axial cutting force.

Above all, cutting force influenced order can be obtained: cutting depth is the largest, followed by the spindle speed, and feed speed is the minimum. It is obvious to see that at large cutting depth, without ice fixation, the cutting force F_z exceeds that of ice fixation one for the first time (Fig. 9c). It indicates that increasing cutting force leads to the horizontal compressive stress increased at the large cutting depth, as well as the aluminum alloy chip appears high temperature viscosity, which is easily stuck on tool cutting edges and rake surface, as shown in Fig. 10a, and the tool wear is also heavier. They all lead to the axial resistance enhancement. While in cryogenic, the temperature rise is inhibited by low temperature medium. And under cryogenic aluminum alloy presents brittleness and less viscosity. Meanwhile, because of the cutting force is not bigger, and the lubrication effect of cryogenic and ice leads to the smaller tool wear which is illustrated in Fig. 10b, the small fixation strength leads to increase the honeycomb deformation degree. Moreover, part of honeycomb cannot be effectively processed, and the cutting surface quality is inclined. In addition, the oscillations of tool and machining surface are intensified through increasing cutting depth. So z direction resistance increases, and the slight decline occur at the y, x ones.

3.4 Processing defects reasons without ice fixation

From the processing results such as surface morphology of without ice fixation as illustrated in Fig. 5, the burr defect mainly appears in head and tail parts of the brazing surface (double layer honeycomb). And the curly and edge collapse defects mainly are seen in the edge of the honeycomb (for single layer honeycomb), as shown in Fig. 5b. On the other

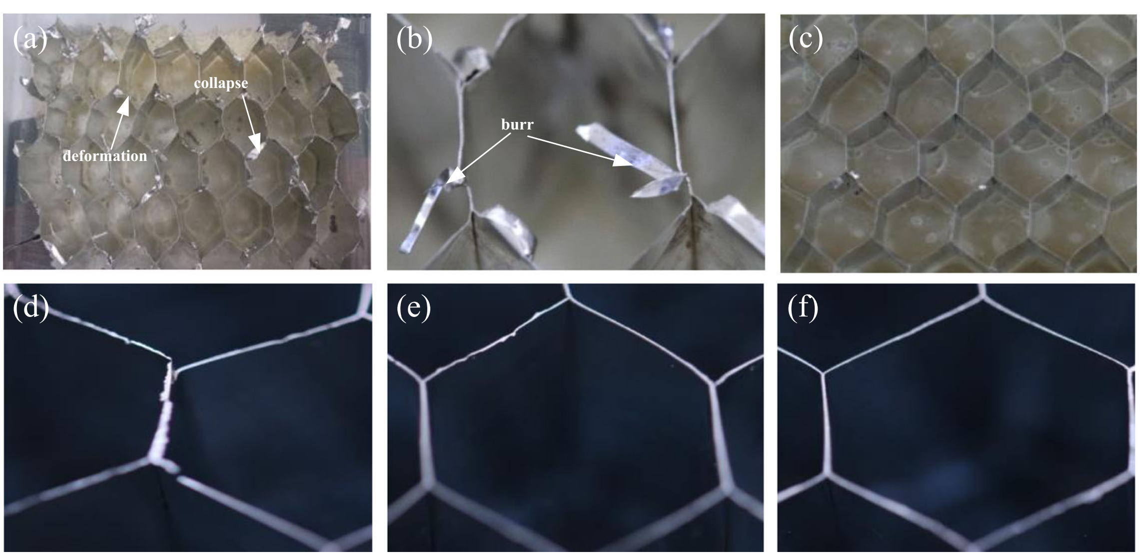

Fig. 5 Processing morphology. **a** Collapse and deformation for no ice fixation processing. **b** Burr for no ice fixation processing. **c** Processing morphology for ice fixation processing. **d** 1000 rpm for ice fixation processing. **e** 4000 rpm for ice fixation processing. **f** 8000 rpm for ice fixation processing

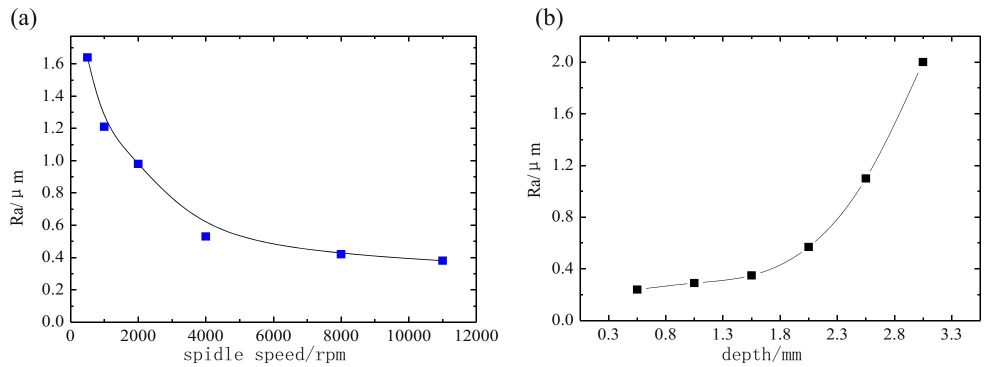

Fig. 6 Ice fixation processing surface roughness. **a** Influence of spindle speed. **b** Influence of cutting depth

hand, as provided in Fig. 5a, the deformation defects mainly are found on the honeycomb edge of the workpiece. The literature [21] demonstrated the analysis results of mechanics properties of the hexagonal honeycomb core. The formula of in-plane elastic mechanics performance parameters of honeycomb could be gotten by the formula (4).

$$E_D = 2E_S = \frac{4}{\sqrt{3}} E_C \left(\frac{h}{l}\right)^2 \quad (4)$$

Due to honeycomb wall thickness, h is only 0.02 mm and the length l is 10 mm. On honeycomb surface, the radial modulus E_D or E_S is only about 10^{-5} of the alloy substrate E_C, which leads to very low in-plane radial strength and serious processing defects.

The following gives the causes of processing defects:

Firstly, the curly and edge collapse defects are provided in edge of honeycomb section of single layer. For the single layer, it has low in-plane radial shear strength and stiffness for thin-walled honeycomb wall. At the same time, there is lower and uniform cutting force which is even not enough to remove metal. This force only could make large area machined surface bending or collapse. So, in this area, the chip breaker is insufficient and curly, and collapse edge defects are leaved inevitably.

Secondly, the honeycomb deformation defects appeared on the honeycomb workpiece edge, and it is attributed to in-plane mechanical characteristics of the thin-walled metal honeycomb. Compared to the central area honeycomb, there is minimum in-plane strength on the edge of workpiece. For the former under the effect of cutting force, it is only small deformation for the processing surface, and the force can mainly be undertaken by the cutting deformation. But on the edge area, the cutting force completely is born by individual or part of the honeycomb. Furthermore, due to honeycomb bottom is fixed, the upper part of the honeycomb has large deformation. While upper hexagon pattern is destroyed, the deformation defect is appeared.

Lastly, when processing the head and tail parts of brazing surface of double honeycombs by means of the honeycomb test results, it is possible to notice that the milling surface at transition sections between single and double honeycomb will suffer from milling force with large gradient. For example, from double transits single layer, milling force will reduce close to a half. Meanwhile, due to the large toughness and strength for metal honeycomb, the cutting force is insufficient and uneven distribution. It causes the increase of cutting vibration. The processed surface is severely stretched, and the tensile fracture is the main type of chip breaker. Meanwhile, the bonding strength of brazing surface on both ends is weaker than in the middle, which causes open welding defects.

In conclusion, the processing defects of alloy honeycomb mainly are attributed to uneven cutting force, as well as the lower in-plane radial stiffness and strength of honeycomb.

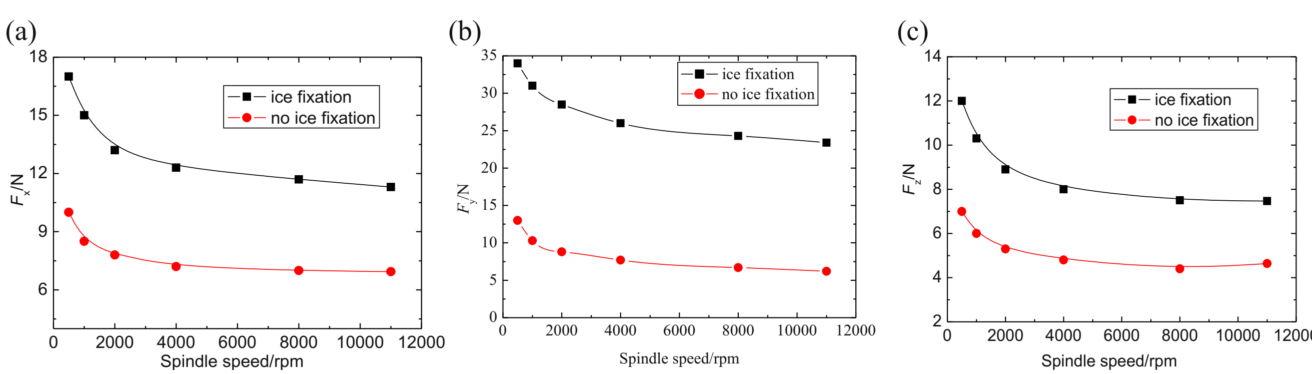

Fig. 7 The effect of spindle speed on milling force. **a** Feed force. **b** Main cutting force. **c** Back force

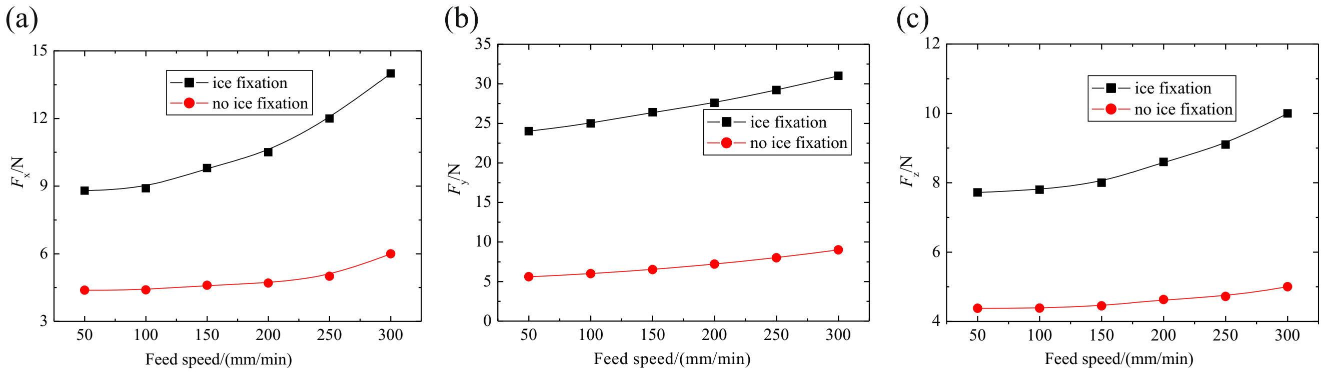

Fig. 8 The effect of feed speed on milling force. **a** Feed force. **b** Main cutting force. **c** Back force

3.5 Ice fixation cryogenic processing mechanism

The SEM surface microstructures are shown in Fig. 11. The processing surface is roughness and the cutting area appears tension fracture as depicted in Fig. 11a. The break micro-area can be broken up into three regions in detail. They will identify different forms of chip breaker, and the cross section surface will also be irregular. The outermost one is obviously relatively smooth. Because of the activity, the alloy is easily oxidized in air, it mainly causes by the brittle oxidation phase Al_2O_3 (Fig. 11b) on the alloy surface with few microns thickness who has shear fracture property. In the second region, the tensile fracture cracks can be caught. Meanwhile, because of the weak rigidity of the honeycomb and the high toughness of alloy, the chip is not easily cutting broken and it is stretched to form cracks. Especially, because of alloy poor thermal conductivity [22, 23], it leads to instant slow dissipation for cutting heat in the third region, and the alloy plastic is increasing. It can deduce that the chip is tensile facture near the outer part and the surface presents uneven curl.

Based on the processing result in cryogenic, due to the liquid nitrogen effect on the cutting area, temperature even can be instantaneously fallen to −196 °C. Relative to without ice fixation at room temperature of the conventional fixation methods [9–13], in cryogenic condition, the honeycomb strength on cutting point is increasing as illustrated in Table 3, especially the yield strength and the tensile strength will increase all more than 20%. The change indicates that the honeycomb brittleness is obviously enhanced. On the other hand, the processed cross section can be acquired by Fig. 11c. It can deduce that the cutting regions consist of uniform compact break layers, and the shear micro-area is well-defined, as well as the fractures are all brittle break state. So the honeycomb chip break type is obviously changed. That is from tensile fracture with producing the crack and crack propagation to shear fracture of brittle material. Therefore, the cutting surface is more smoother compared to that of without ice, and the burr defect is suppressed. Consequently, the surface quality is clearly improved.

Furthermore, honeycomb fixation force is similar to the clamping force. The bonding strength in three direction of without ice fixation is 98, 98, and 42 N as shown in Table 2, respectively. But the forces only act on the bonded surface and that is far away from the adhesive surface. The fixation strength on machining surface is very small, and it is far less than cutting force, and it even can be ignored. So, it is easy to cause processing defects. Because the ice fixation forces reach 287, 287, and 245 N (Table 2) in three directions, they are distributed uniformly and bigger than cutting force. Besides, the thin-walled honeycomb materials in ice fixation are similar to the resin enhanced aramid fiber material. Due to under −50 °C, the compressive strength of the ice can keep in 1.3 MPa. Meanwhile, the radial compressive strength is very low, even it is just scores Pa for the thin-walled workpiece.

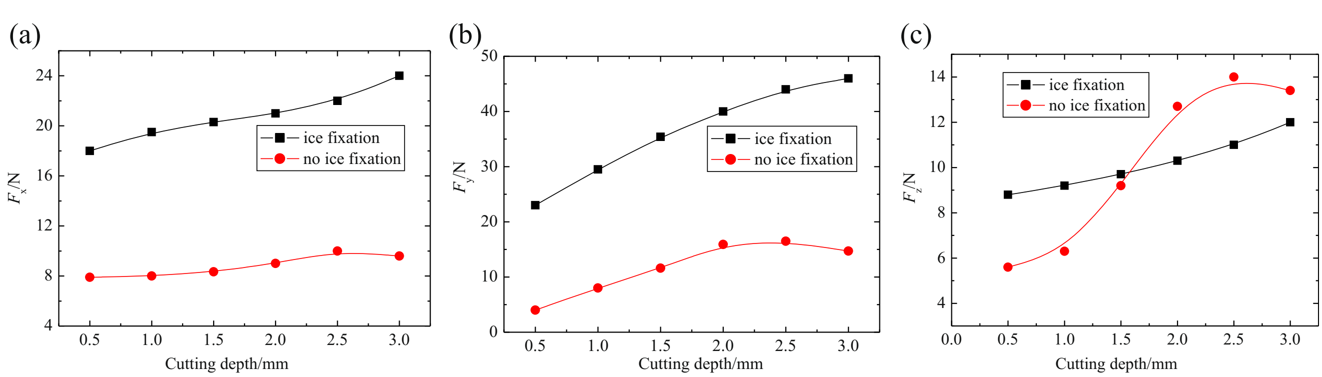

Fig. 9 The effect of cutting depth on milling force. **a** Feed force. **b** Main cutting force. **c** Back force

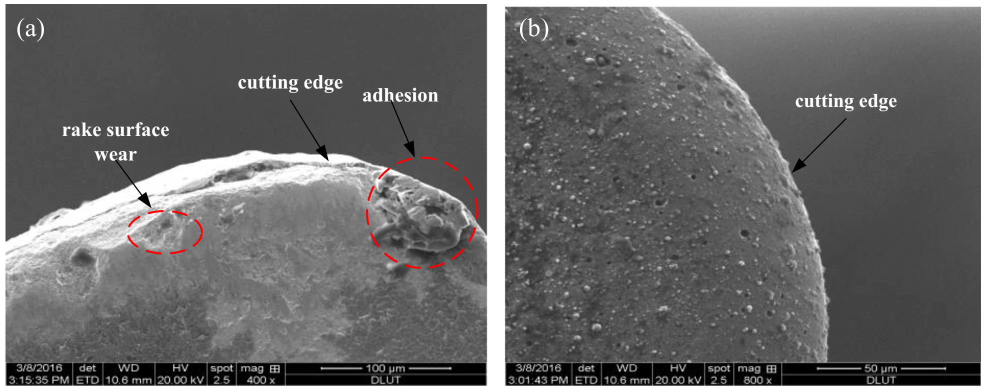

Fig. 10 Tool wear. **a** Without ice fixation. **b** Ice fixation cryogenic

Obviously, the radial compressive strength of honeycomb is increased rapidly. Honeycomb fixation effect is enhanced and that inhibits the deformation factors in processing. At the same time, the fixation force is uniform distribution, and in each area of the processed honeycomb, it is homogeneous with no deformation.

Last but not least, at processed points, it appears a pressure shortage phenomenon by the cutting edge. The honeycomb has not been effectively chip breaking. In addition, because of the low radial stiffness of honeycomb itself, the honeycomb presents an instant elongation and automatic collision avoidance properties, and the burr defect is also inevitable. But for ice fixation in cryogenic, due to high strength of alloy as well as high hardness of ice, the composite strength is increased, and the cutting force is also enhanced sharply, as shown in Fig. 9. There reaches even about three times under the same cutting parameters for the biggest change. As a result, the increasing of cutting force is also largely solved the deficient problem of cutting force, and burr defect can be effectively suppressed.

4 Conclusions

Based on the methodology applied on the present comprehensive comparative investigation, the following conclusions can be claimed. Firstly, compared to the fixation force and strength of the without ice or conventional fixation way, the ice fixation

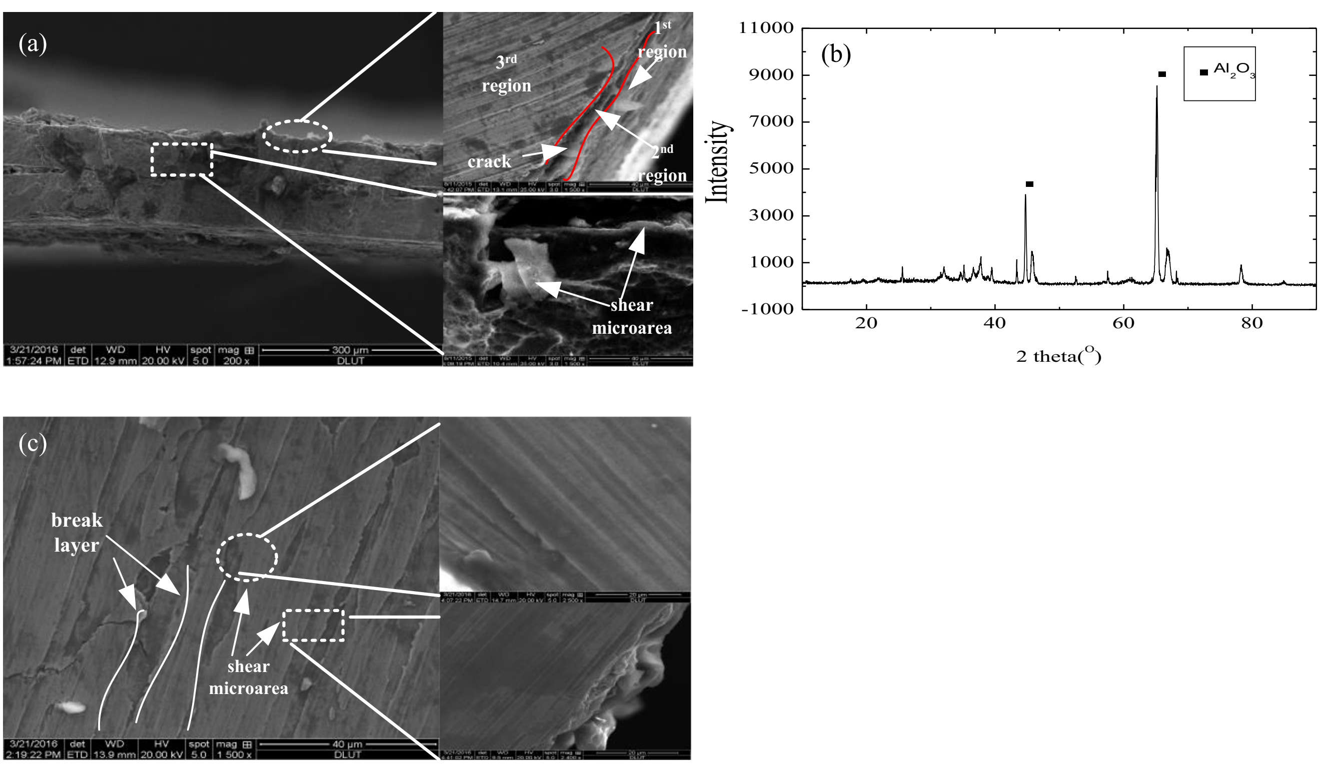

Fig. 11 The SEM surface microstructure and phase. **a** No ice fixation. **b** Phases of honeycomb surface. **c** Ice fixation

Table 3 7075 aluminum alloy properties in different temperature [21–23]

Temperature/°C	Yield strength/MPa	Tensile strength/MPa	Elasticity modulus/GPa	Elongation/%
20	554.3	612.2	70.7	18
−196	695.6	764.6	77.3	18

ones have all greatly increasing and that can reach 287 N and 19.1 kPa, and they can satisfy with the honeycomb milling process. The ice fixation cryogenic milling of aluminum alloy honeycomb has a great improvement at the same time, and the cutting depth has a greater influence on surface quality than other process parameters. The milling force is much more improved than the conventional way with the highest reaching three times. The order of the parameters effect on the force is that: cutting depth is the largest, followed by the spindle speed, the feed speed has the minimal impact. Secondly, the improvement of fixation and milling force and the cryogenic processing are the main reason of reducing defects. Meanwhile, the cryogenic can make the way of chip breaker transformed from tensile fracture into rigid shear way. Lastly, the new process suppresses the machining defects and provides a new and high-efficient machining method for the thin-walled metal honeycomb materials. All kinds of honeycomb workpieces with complication shape and structure can precisely processed and obtained like other solid workpiece through CNC machine using the advantage process. Furthermore, the green processing way will be widely used in the aerospace manufacturing for other honeycombs through suitable process parameters.

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