Cutting Force Investigation when Heavy Milling Welded Aluminum-Thin-Walled Hollow Structure

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Abstract. Commercial cutting tools of sintered high speed steel and carbide were used to heavy milling 6N01-T5 aluminum thin-walled hollow W-shape structures under four kinds of cooling conditions. The results showed that the cutting forces increased dramatically when cutting the weld seam or the intersectant ribbed slab where the value of cutting forces were over ten times bigger than those of cutting the single ribbed slab. Among the four cutting parameters, radial depth of cut was the most significant influence factor and followed by feed rate and axial depth of cut. Spindle speed had a less influence. The optimum combination of cutting parameters for the cutting vibration experiments was 3000 rev/min for the spindle speed, 0.05 mm/tooth for the feed rate, 5 mm for the axial depth of cut and 5 mm for the radial depth of cut. The results also showed the order of the effectiveness of the cooling methods on reducing the cutting force was cryogenic pneumatic mist jet impinging (CPMJI), pneumatic mist jet impinging (PMJI), cryogenic wind and dry cutting.

Introduction

Aluminum alloy is generally classified in the category of easy-to-cut materials. However, due to the low matrix hardness, high ductility and sticky nature, high chemical activity of the aluminum alloy, there are many machining problems such as tool irregular wear, sever adhesion on the tool face and burrs and marks of pressing/extrusion on the machined surface [1-2]. These problems have a great influence on the efficiency, quality and cost when machining this kind of material. Furthermore, heavy cutting method was generally used when machining aluminum structures so as to improve the efficiency [3]. This causes a high level of cutting force and cutting temperature which leads to the generation of obvious build-up-edge or the melt of the aluminum alloy [3-4]. In this case, a effective cooling method is needed to reduce the cutting temperature. However, the regular cooling method which often uses the regular coolant liquid with large rate of flow may cause the oxidization on the surface of the aluminum alloy and the contamination by the cutting oil which has a detrimental effect on the subsequent welding process of the parts [4]. The expensive special coolant is often applied when heavy machining aluminum alloy structures, which in turn greatly increases the machining cost [5].

In the recent ten years, a quantity of researches have been done on the high/ultra-high speed machining on aluminum alloys but little attention has been given to the study on the heavy cutting frames or thin-walled structures under the medium or low cutting speed [6-13]. For these special structures, a combination cutting parameters of very big axial and radial depth of cut, very high feed rate was often selected when machining [7-8]. The common characters of these special structures are the low stiffness and the high value of cutting temperature, force and vibration [10]. Therefore, a poor machining quality is often obtained and the tool wear rate and the cost of cutting tool are high when compared to the machining of aluminum sheet [11]. Cutting force has an intimate relationship with the cutting vibration, cutting temperature and tool wear patterns [11-13]. In this investigation, a 6N01-T5 aluminum thin-walled hollow W-shape structure was selected as the workpiece and several kinds of commercial cutting tools were used to investigate the cutting forces and these influence factors under the heavy milling condition.

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Experimental Work

Materials and Machine Tools

Sample of dimensions 240 x 100 x 60 mm of 6N01-T5 aluminum thin-walled hollow W-shape structure was selected for the experiment. The thickness of the single ribbed slab (aluminum alloy sheet) is 2.5-3 mm. The cutting tools used were sintered high speed steel (LMT^{TM}) and carbide (DIJET^{TM}) cutters with a diameter of 20 mm. Tool materials and the specifications are tabulated in Table 1. All the milling tests were conducted on the DMG DMC70V hi-dyn milling center.

Tab.1 Details of the cutting tools

Tool supplier	Rake angle[^{o}]	Flank angle[^{o}]	Helix angle[^{o}]	Flutes
DIJET	20	12	45	2
LMT	5	10	30	3

Experimental Scheme

The workpiece sample was fixed on a backing plate with two clamps and the plate was connected to the Kistler 9272 four component piezoelectric dynamometer by six screws below which was the worktable of the machine tool (Fig.1). The positive direction of the cutting forces *Fx* (radial component), *Fy* (feed component), *Fz* (axial component) was corresponding to the positive direction of X axis, the negtive direction of Y axis and the negtive direction of Z axis, respectively, as shown in Fig. 1. The sampling frequency of cutting forces acquisition was set at 10 kHz and the low pass filter with a frequency of 100 Hz was used.

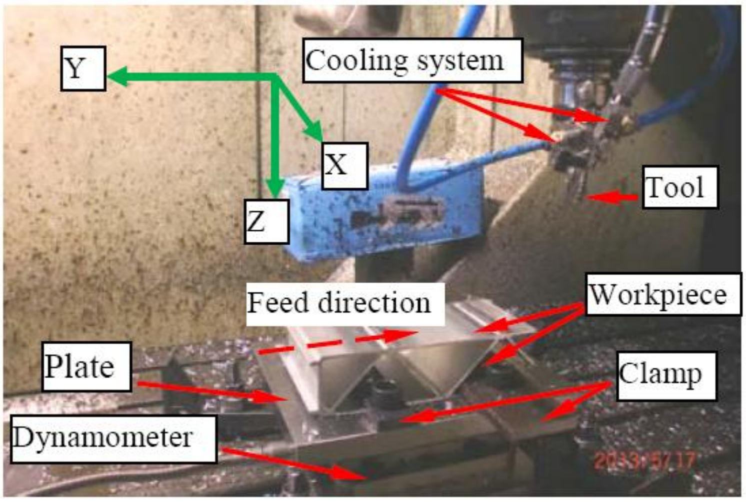

Fig.1 Workpiece and the experimental work

The cooling system is shown in Fig.2. As observed, the condition of cryogenic pneumatic mist jet impinging cooling (CPMJI) can be obtained when all the valves of the cooling system are open. When the valve of the cooling gun is shut down, a pneumatic mist jet impinging cooling (PMJI) condition can be obtained. The cryogenic wind can be acquired when only using the compressed air and the cooling gun. Hence, the effect of cooling condition (dry, cryogenic wind, PMJI and CPMJI) on the cutting vibration can be compared.

The Taguchi method was used in the experiments design of cutting vibration study (Tab.2). The orthogonal array selected was the L_9 (4^3) corresponding to 4 parameters with 3 levels each as shown in Tab.3. The outputs studied was the resultant cutting force *F* which equals to the root of the sum of the three component *Fx*, *Fy*, *Fz*. The treatment of the experimental results was based on the analysis of signal-to-noise (S/N) ratio.

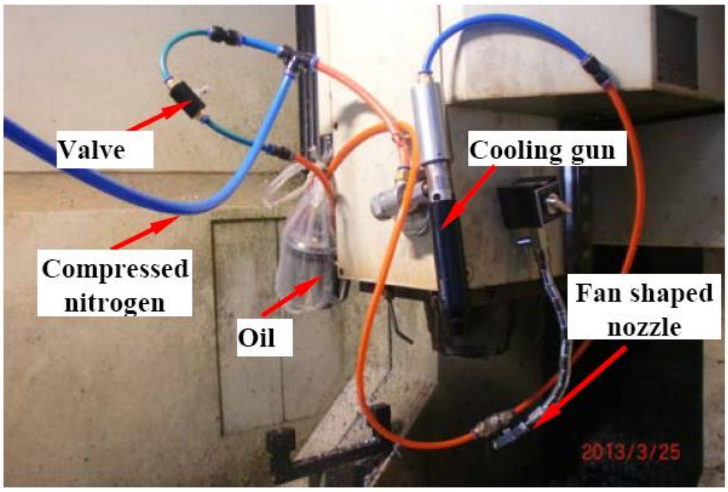

Fig. 2 The cryogenic pneumatic mist jet impinging cooling system

Tab.2 Cutting parameters and their levels (DIJET, Dry cutting)

Symbol	Cutting parameters	Unit	Level 1	Level 2	Level 3
A	Spindle speed	rev/min	8000	5000	3000
B	Feed rate	mm/tooth	0.2	0.1	0.05
C	Axial depth of cut	mm	20	10	5
D	Radial depth of cut	mm	5	10	20

Tab.3 Three-factor three-level (L_9)Taguchi orthogonal table

Test number	Spindle speed *N* [rev/min]	Feed rate f_z [mm/tooth]	Axial depth of cut a_p[mm]	Radial depth of cut a_w [mm]
No.1	8000	0.2	20	5
No.2	8000	0.1	10	10
No.3	8000	0.05	5	20
No.4	5000	0.1	20	20
No.5	5000	0.05	10	5
No.6	5000	0.2	5	10
No.7	3000	0.05	20	10
No.8	3000	0.2	10	20
No.9	3000	0.1	5	5

The goal of the study is to optimize the milling parameters to get lower cutting forces so as to reduce the tool wear rate, the cutting vibration and the surface roughness value. Thus, the observed values of forces were set to minimum. That means that the objective function, S/N ratio, is calculated based on the-smaller-the-better characteristic, which can be calculated as:

$$\frac{S}{N} = 10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{1}$$

where y_i is the observed data and n is the number of observations.

Results and Discussion

Analysis on the Typical Cutting Forces Signal

As can be observed from Fig. 3, the cutting forces increased dramatically when the tool cut at the area of weld seam or the intersectant ribbed slab where the value of cutting forces was three to ten times bigger than that of cutting the single ribbed slab (aluminum alloy sheet), as shown in Fig. 4. This is due to the fact that the actual axial depth of cut increases abruptly (by 100%-600%) when the tool cuts at these area. What's more, as soon as one of the ribbed slab is cut through, the local rigidity of the thin-walled hollow structure decreases greatly, which results in bigger cutting vibration. This in turn resulted in the abrupt increase of cutting forces. It is noted that the workpiece is the W shaped structure which results in the periodicity of the cutting forces and cutting vibration. The periodic cutting vibration has a detrimental effect on the tool wear especially on the adhesive wear of the tool.

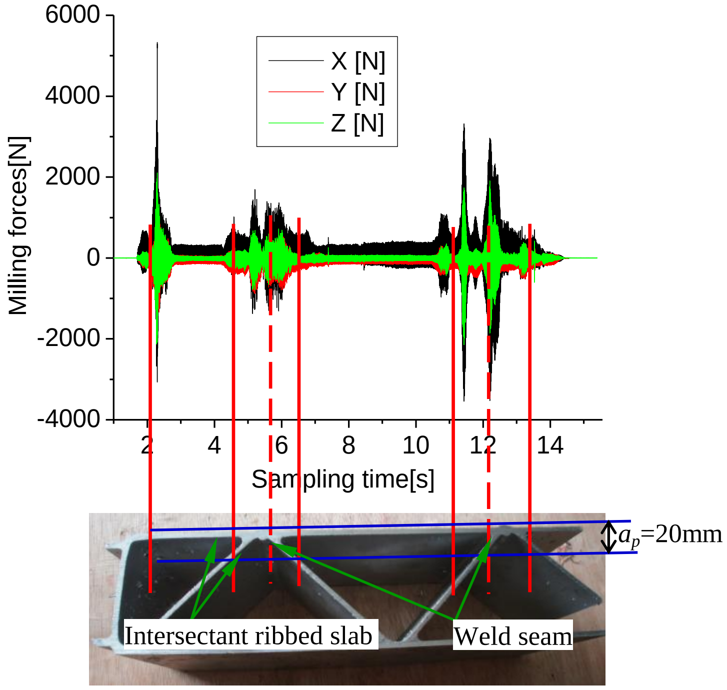

Fig.3 The typical cutting forces signal for the welded aluminum-thin-walled hollow structure (LMT, N=5000 rev/min, f_z=0.1 mm/tooth, a_p=20 mm, a_w=20 mm, PMJI cooling)

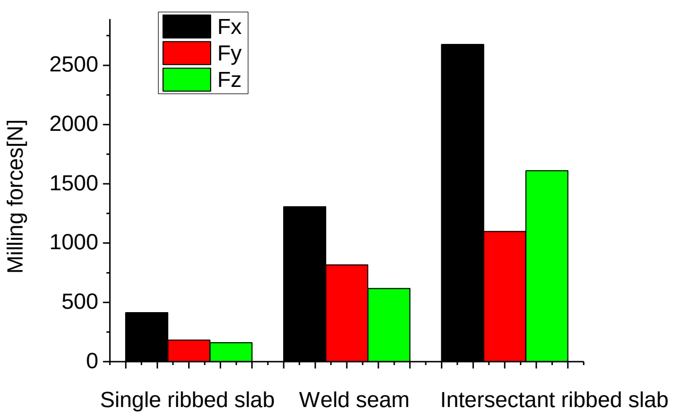

Fig. 4 Three component forces when the tool cut different structure of the workpiece

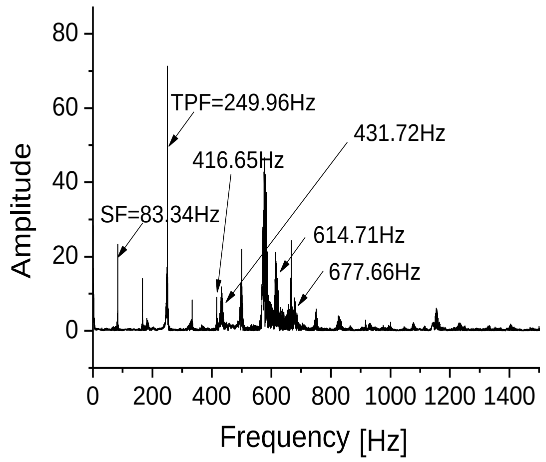

Fig.5 The Spectrum of milling force signal Fx in Fig.3

As can be observed from Fig.5, besides the spindle revolution frequency SF and the tool periodic cutting frequency TPF and their Harmonic component, there are also some other high frequency component such as the frequency of 416.65Hz, 431.72Hz, 614.71Hz and 677.66Hz which indicates that the thin-walled hollow W-shape structure itself have made a considerable contribution on the cutting forces and the cutting vibration.

Influence of Cutting Parameters on Cutting Force (Analysis of the S/N Ratio)

Tab.4 shows the experimental results for cutting force and the corresponding S/N ratio. The mean S/N ratio for each level of the three cutting parameters is summarized and called the S/N response table for cutting force (Tab.5). In addition, the different values of S/N ratio between maximum and minimum for the three levels of each factor are also calculated and listed in Tab.5. Fig.6 shows the S/N response graph for cutting force. According to Tab.5 and Fig. 6, factor D (radial depth of cut) has the highest difference between maximum and minimum values 4.79 and this is followed by factors B (feed rate) and C (axial depth of cut) which have the difference values 4.54 and 4.33, respectively. Factor A (radial depth of cut) has the lowest difference value 0.75. Thus, it can be concluded that the significance order of the influence factors is radial depth of cut, feed rate, axial depth of cut and spindle speed based on the Taguchi prediction that the larger different between value of S/N ratio will have a more significant effect on cutting force (*F*). It is observed in Fig.6 and Table 5 that level 3 of A factor (spindle speed), level 3 of B factor (feed rate), level 3 of C factor (axial depth of cut) and level 1 of D factor (radial depth of cut) are lower. Consequently, the optimum cutting conditions determined under the same conditions for the cutting force experiments to be conducted will be 3000 rev/min for the spindle speed, 0.05 mm/tooth for the feed rate, 5 mm for the axial depth of cut and 5 mm for the radial depth of cut.

Tab.4 Experimental results for cutting force and S/N ratio

Test number	No.1	No.2	No.3	No.4	No.5	No.6	No.7	No.8	No.9
Cutting force *F*/ (N)	1800	1441	1126	2300	767	1702	1523	2059	738
S/N ratio /dB	65.10	63.17	61.03	67.23	57.69	64.62	63.65	66.27	57.36

Tab.5 S/N response table for cutting force

Symbol	Cutting parameters	Mean S/N ratio(dB)			
		Level 1	Level 2	Level 3	Max-Min
A	Spindle speed	63.10	63.18	62.43	0.75
B	Feed rate	65.33	62.59	60.70	4.54
C	Axial depth of cut	65.33	62.38	61.0	4.33
D	Radial depth of cut	60.05	63.81	64.84	4.79

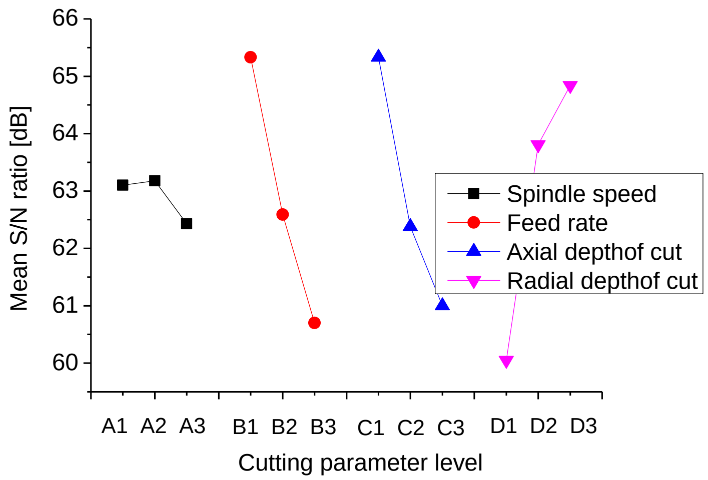

Fig.6 S/N response graph for cutting force

The non-linear multiple regression analysis method has been deployed to analyze the cutting force in the form of empirical equation. Based on the datum from Table 4, the empirical equation of cutting force obtained is as follows:

$$F = 293.42n^{0.08} f_z^{\ 0.38} a_p^{\ 0.36} a_w^{\ 0.40}, \ R^2=0.94, \ F=16.4 \tag{2}$$

It is observed from Fig. 6 and Eq. (2) that spindle speed has a little effect on the cutting force and that increasing the spindle speed appropriately in a certain range (such as increasing from 3000rev/min to 8000rev/min) will significantly increase the material removal rate while only slightly increase the cutting force.

Influence of Cooling Condition on Cutting Vibration

Fig.7 shows that, for the five kinds of cooling conditions used, the use of CPMJI produced the lowest value of cutting force and this is followed by using PMJI. Fig. 7 also shows that the value of cutting force is bigger under cryogenic wind cooling than under oil cooling (PMJI), which indicates that the lubrication effect is more important than the cooling effect as far as cutting force is concerned when heavy mill 6N01-T5 aluminum thin-walled hollow W-shape structure.

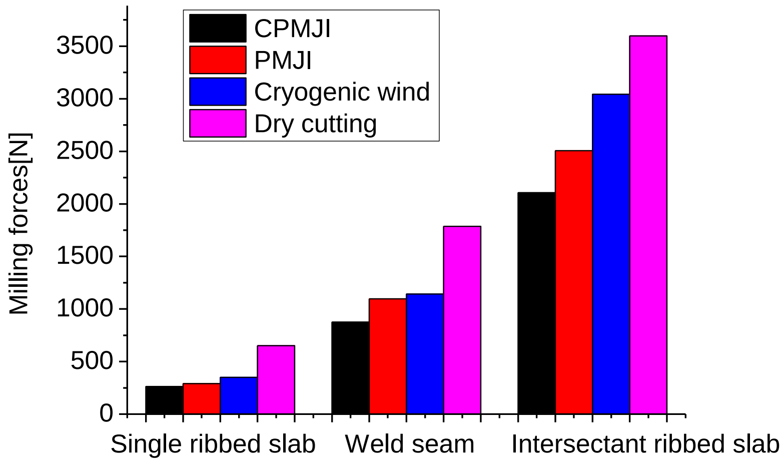

Fig.7 The effect of cooling condition on the cutting force (DIJET, N=5000 rev/min, f_z=0.1 mm/tooth, a_p=20mm, a_w=20mm)

Conclusions

(1) The cutting force increases dramatically when the tool cut at the area of weld seam or the intersectant ribbed slab where the value is three to ten times bigger than that of cutting the single ribbed slab. Besides the spindle revolution frequency and the tool periodic cutting frequency, the thin-walled hollow W-shape structure itself have made a considerable contribution on the cutting forces and the cutting vibration.

(2) Radial depth of cut was the most significant influence factor and followed by feed rate and axial depth of cut. Spindle speed had a insignificant influence. The optimum combination of cutting parameters for the cutting force experiments was 3000 rev/min for the spindle speed, 0.05 mm/tooth for the feed rate, 5 mm for the axial depth of cut and 5 mm for the radial depth of cut.

(3) The use of CPMJI and PMJI can effectively reduce the cutting force and CPMJI produced the lowest value of cutting force and this is followed by using PMJI. The use of cryogenic wind or oil can also reduce the cutting force to a certain extent, however, the use of oil is more effective than using of cryogenic wind.

Acknowledgment

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