Effect of Machining Processes on Surface Quality of 7075Al Alloy Fastener Holes

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Abstract　To achieve the required surface characteristics, the experiment and simulation researches on effects of drilling processes on surface quality of aircraft fastener holes drilled on 7075-T7351Al alloy were conducted from the perspective of surface integrity and fatigue life. Compared conventional multi-step drilling processes with Winslow, it is found that there are smaller roughness vales (*Ra*), less operation defects, larger compression residual as well as higher fatigue strength on the machined surfaces produced by multiple-step with slow feed (DBM) and Winslow, and *Ra* of Winslow is lower than 60%, fatigue limit is 23% higher than that of DBM. Based on test data, two empirical formulas affecting roughness and residual stress are established, and strain distribution and temperature variation are analyzed by numerical simulation. In addition Winslow strengthening mechanism are discussed. It is put forward that appropriate increase in cutting speed or decrease in feed rate can improve surface quality of fastener hole.

Key words　7075-T7351Al alloy, Surface integrity, Fatigue life, Fastener hole, Machining process, Winslow technology

加工工艺对7075铝合金紧固孔表面质量的影响

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文　摘　为确定最佳制孔工艺、获得理想表面特性，从表面完整性和疲劳寿命角度对7075铝合金飞机紧固孔表面质量进行了实验性和数值仿真研究。通过比较常规多步制孔和钻扩铰一步复合工艺(Winslow)，发现钻扩铰多步慢进给工艺(DBM)和Winslow所产生的表面具有较小的*Ra*值，较少的加工缺陷、较大的残余压应力及较高的疲劳强度，而后者的*Ra*值低于前者60%，疲劳寿命高于前者23%；基于实验数据，建立了切削参数对表面粗糙度和残余应力影响的经验公式；应用数值仿真分析了加工过程中应变和切削温度的变化规律；探讨了Winslow工艺的强化机理；指出适当减少进给量、增加切削速度能够提高紧固孔的表面质量。

关键词　7075-T7351铝合金，表面完整性，疲劳寿命，紧固孔，制孔工艺，Winslow技术

0　Introduction

Fastener holes used for connection or rivet various parts are indispensable structure details of aircraft manufacturing. Fatigue failure being one of the most common injured forms in service aircraft structures, surface quality of fastener holes will affect directly safety and reliability of aircraft [1-2]. Currently traditional multi-step drilling is widely applied for aircraft existing assembly. However, it is difficult to ensure working quality of holes with the improvement of the technical requirements, so Winslow technology is introduced from abroad. But because of its expensive price and difficult sharpening for tool, this process has not been fully verified and the practical application has not been promoted. Now many investigations on surface quality of aircraft fastener holes are carried out. The internal contacts between drilling machining and initial fatigue quality are studied. Some methods selected or validated drilling

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techniques are given by compliance check[3]. An expert system with corresponding detection and appraisal technology is set to implement durability evaluation and coincidence check[4-5]. Moreover, it is discussed that influence of structure details design and cutting parameters on the initial fatigue quality and fatigue properties[6-9]. However, above researches are mainly focused on how to control the equivalent initial crack of fastener holes, set up fatigue life evaluation system, while there are fewer studies on the effects of machining processes on surface quality. The goal of this paper is to identify a relationship between surface quality, drilling machining and fatigue behavior of 7075-T7351Al alloy in order to determine the best process parameters and control holes surface quality. So this work has great practical significance.

1 Experiments

1.1 Material and mechanical properties

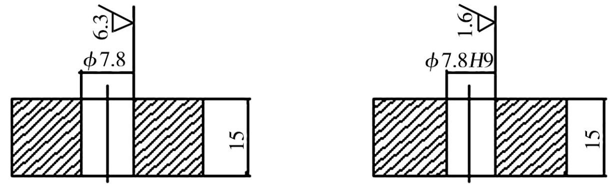
The studied material is 7075-T7351Al alloy, being good structural material in the aerospace industries, used for aircraft wing beams, skin and subjected to high stress and frequency variable loads. The mechanical properties of this material are listed in Tab. 1.

Tab. 1 Mechanical properties of 7075-T7351 Al alloy

tensile strength /MPa	yield strength /MPa	elongation /%	hardness (HV)	fatigue strength /MPa
540.96	475.30	11.5	113	160

1.2 Structures and technical demands

Fastener holes with diameter of 7.8 mm and thickness of 15 mm were drilled on 7075-T7351Al alloy rolling specimens and used for connecting or riveting various parts. The structures, sizes and technical demands of the holes are given in Fig. 1.



(a) Connect hole produced in drilling (b) Rivet hole generated in dring and reaming multiply-step or in one-step compound cutting

Fig. 1 Structures and technical demands for fastener holes

1.3 Experimental set-up

Experimental works were carried out under cutting conditions provided by Tab. 2.

Tab. 2 Drilling processes and cutting parameters of fastener holes1)

process name	code No	main procedures	process step/mm	cutting capacity: turning speed /r·min^{-1}	feed rate /mm·r^{-1}	cutting speed /m·min^{-1}	coolant
air-drilling-manual drilling-fast feed	ZBK	one-step drilling-three-step reaming	drilling Φ3.0	2100	*	31.8	unusing
			reamin Φ6.2	1300	0.14		
			Φ7.6	1300	0.14		
			Φ7.8	1300	0.14		
air-drilling-manual drilling-slow feed drilling & reaming	ZBM	one-step drilling-three-step reaming	drilling Φ3.0	2300	*	52.7	unusing
			reamin Φ6.2	2150	0.04		
			Φ7.6	2150	0.04		
			Φ7.8	2150	0.04		
drilling & reaming-multiply-step with fast feed	DBK	one-step drilling-two-step reaming-three-step reaming	drilling Φ3.0	2100	0.14	19.6	unusing
			reamin Φ6.2	1300	0.14		
			Φ7.3	1300	0.40		
			reamin Φ7.6	800	0.40		
			Φ7.7	800	0.40		
			Φ7.8	800			
drilling & reaming-multiply-step with slow feed	DBM	one-step drilling-two-step reaming-three-step reaming	drilling Φ3.0	2300	*	34.3	unusing
			reamin Φ6.2	2150	0.04		
			Φ7.3	2150	0.04		
			reamin Φ7.6	1400	0.10		
			Φ7.7	1400	0.10		
			Φ7.8	1400	0.10		
one-step-compound cutting(Winslow)	YR	drilling & reaming one-step compound cutting	Φ7.8	3600	0.05	88.2	T80-92B

Explenant: 1) " * " Needing withdraw drill to remove chip and being liable to break drill, data of Φ3.0 feed did not be measured.

The surface topographies of all groups specimens were observed under scanning electron microscope (SEM), and the values of surface roughness Ra were measured with surface profiler. The residual stress distributions were determined by using X-ray stress analyzer type and electrolysis to 0.1 mm layer thickness measurements. Fatigue tests were conducted on the Instron 8802 fatigue test machine, with load control, fatigue load spectrum for the sine wave cycle of load, stress ratio $R=\sigma_{min}/\sigma_{max}=0.06$, loading frequency $f=6$ Hz, the maximum nominal stress is 130, 150, 170 MPa.

2 Results and discussion

2.1 Effect of machining on surface integrity

(1) Surface roughness Surface roughness is an important factor evaluating surface quality[10-11]. All average Ra data recorded from each cutting condition are presented in Fig. 2.

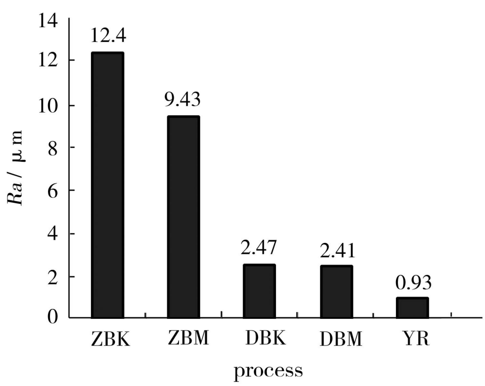


Fig. 2 Effect of drilling processes on Ra

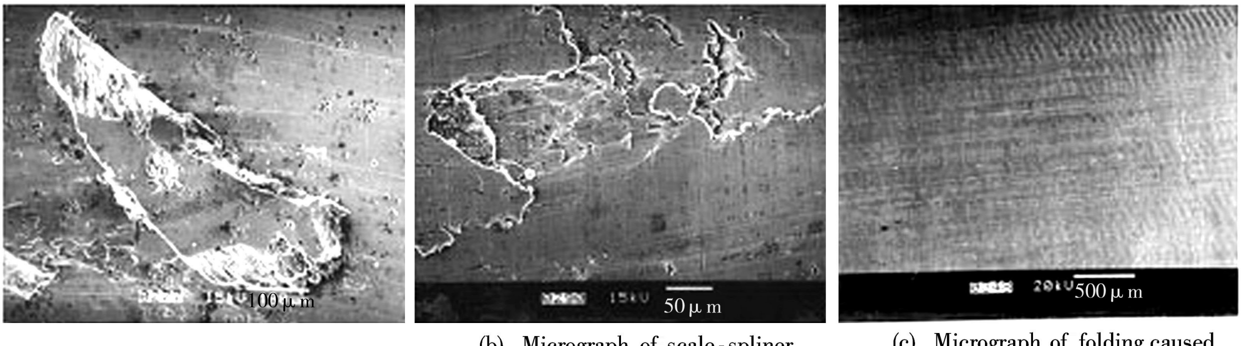
Fig. 2 indicates that the order level of Ra values employed by five drilling processes from high to low is ZBK>ZBM>DBK>DBM>YR, and these levels are divided into three grades, from 12.4 to 9.44 μm, 2.47 to 2.41 μm and 0.93 μm. Roughness obtained by YR is the lowest, followed by is DBM, and the former is lower than the latter about 60%. From these results, it can be conducted that surface quality generated by YR is superior to that of other drilling processes. Moreover, among DBK, DBM and YR, only Ra value of YR is equal 0.93 μm enough to meet the design requirements ($Ra=1.6$ μm), while others can not be satisfied.

There are many factors affecting surface roughness during machining, including cutting parameters. According to measured data, an empirical formula is set up (shown Eq. 1) by applying regression

$$Ra = 3.36 f^{1.13} v^{-0.065} \quad (1)$$

Where f is the feed rate (mm/r) and v is the cutting speed (m/min). Eq. (1) shows that the feed rate and cutting speed have important influence on surface roughness. Appropriate increase in cutting speed or decrease in feed rate will reduce Ra values.

(2) Machining defects The microscope images of layer underneath the machined surface show that there are many such defects as built-up-edge (BUE), scale-splinter and folding produced by ZBK, ZBM and DBK with fast feed (Fig. 3). The reasons leading to such results may be due to high-level cutting condition, which enable holes to deposit or tear on the machined surface. In contrast, there are less defects on surfaces produced by DBM, YR, and their surface images are flat and smooth. Because these defects induce surface roughness and deteriorate surface conditions, it is necessary to select the appropriate v and f, avoid the scope of BUE formation, and reduce cutting forces and plastic deformation during process.



(a) Micrograph of BUE (b) Micrograph of scale-spliner on surface layer (c) Micrograph of folding caused by vibrating

Fig. 3 Micrographs of the machining defects

(3) Residual stress The measurement residual stress was performed by degrees in 0 mm, 0.1 mm, 0.2

mm and 0.3 mm beneath machined surface. Each was tested for five times. The average result was recorded, and their distributions were described (Fig. 4).

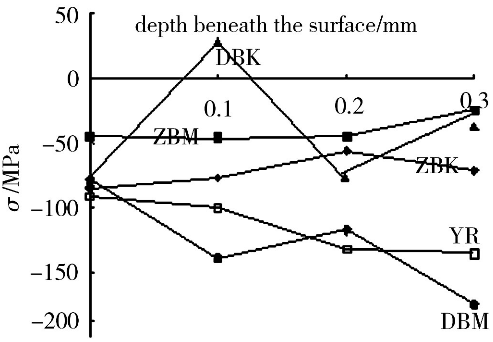


Fig. 4 Residual stresses distribution

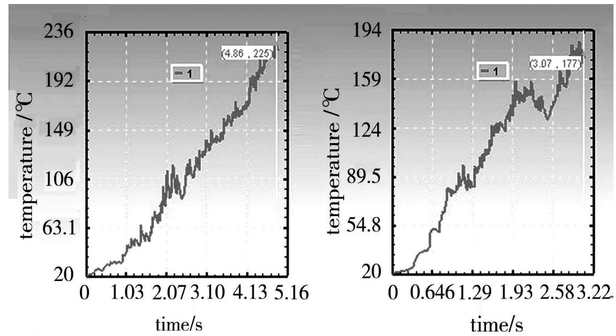
Fig. 4 shows that residual stresses are almost compressive. Stress values of DBM, YR increase gradually along depth beneath surface layer, while that of other processes is decreasing. Moreover, there is a larger fluctuation for DBK, that is the compressive residual stress from machined surface to its maximum tensile value at a depth of 0.1 mm , then it reduces to maximum compressive value at a depth of 0.2 mm beneath the machined surface. As far as the nature of residual stress values is concerned, the surface conditions generated by DBM and YR have great ability to resist fatigue failure due to high withstanding alternating loads. Whether ZBK, ZBM or DBK, DBK, YR has the same characteristics, that the faster the feed is, the larger stress dispersion is, and vice versa. Above detection results may be two reasons[12-14] as follows:

1) Cutting parameters An empirical formula is derived from regression method based on measurement data, shown in Eq. (2).

$$\sigma = 18.34 f^{-1.47} v^{-0.85} \qquad (2)$$

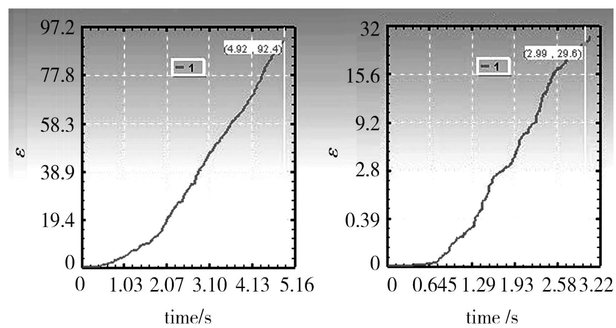
The Eq. (2) implies f and cutting v affect the residual stress, and effect of f is greater than that of v. There are higher stress values of compressive residual under machined surface obtained by YR and DBM.

2) Thermal deformation Residual stresses are also the result of plastic deformation caused by cutting thermal during machining, and the thermal deformation, in turn, affects the residual stresses beneath the machined surface, which should not be ignored. The variations of surface temperatures and deformation produced by different processes are presented in Fig. 5 and Fig. 6 by numerical simulation.



(a) DBK (b) YR

Fig. 5 Distribution of cutting temperature



(a) DBK (b) YR

Fig. 6 Distribution of thermal deformation

Simulation results illustrate that the temperature on machined surface caused by DBK is always higher than that of YR. The highest peak of cutting temperature of the former is 225℃ and that of the latter is 177℃ (Fig. 5). It is also noted that the cutting strain in fast feeding process is obviously higher than that of Winslow process. The peak value of the former is 92.4 and that of the latter is 29.6 (Fig. 6). Cutting thermal and temperature are two main parameters evaluating the machining process. The cutting heat will result in greater thermal stress and deformation, and then lead to increase in residual stresses. The above test results are proved fully.

2.2 Influence of machining on fatigue life

The fatigue tests of fastener holes were complied based on above conditions, and $N_{\mathrm{DB}i}$ is regarded as the fatigue life brought about by multi- step machining processes, while $N_{\mathrm{W}i}$ is considered as that caused by Winslow. The results are shown in Tab. 3. Tab. 3 indicates that $N_{\mathrm{W}i}$ in three stress levels is always larger than $N_{\mathrm{DB}i}$ of DBM and DBK.

Tab. 3 Test results of fatigue life on fastener holes[1)]

No.	L (130/MPa)		M (150 /MPa)		H (170/MPa)	
	N_{DBi}	N_{Wi}	N_{DBi}	N_{Wi}	N_{DBi}	N_{Wi}
1	120290	146631	89241	60869	38416	52413
2	123360	188944	20791	89551	30778	51706
3	141020	179377	70021	82115	34136	74336
4	77472	146679	49945	61371	30667	86020
5	137150	199654	45883	94635	53686	56076
6	92886	179162	42766	49866	48375	53732
7	123540	142133	87864	99693	59215	51105
8	146630	214310	60809	69957	34444	56233
9	135718	147335	45396	55670	63975	42193
10	141863	180029	48237	92261	53862	62186

Note: 1) L, M, H is represented stress levels respectively with low, medium and high. Unit of the fatigue life is cycle.

2.3 Enhancement mechanism of Winslow

Experimental results show that Winslow can improve surface integrity and fatigue life of fastener holes. The main reasons are the following.

(1) Winslow are applied with advanced drilling-reaming compounded tool, and finished machining in one-step. There are small corner radius and good quality grinding for tool as well as low surface roughness. As known from fracture mechanics, the processed surface can be seen as the numerous of micro-gaps, and influence of these micro-gaps on fatigue life can be expressed by theoretical stress concentration factor K_t as follows: shown in Eq. (3)

$$K_t = 1 + 2\sqrt{\gamma \frac{h}{\rho}} \tag{3}$$

Where h is height of roughness, ρ is radius of curvature, γ is the correlation coefficient between space length and height of roughness. The Eq. (3) explains that the stress concentration is not easy to be formed with small roughness and larger curvature.

(2) Compared with other processes, Winslow has a high cutting speed, the smaller feed rate, combined with lubricant. Therefore it can reduce greatly the friction and wear between tool flank and the machined surface, enhance hole working quality.

(3) Surface quality produced by Winslow are ensured mainly by the tool, without the operator's emotions, sense of responsibility constraints. So machining error diffusion is small, and it is easy to control effectively initial fatigue quality of fastener holes.

3 Conclusions

(1) The machining processes and their parameters influence surface integrity and fatigue behavior of aircraft fastener holes, which lead to different developments of microstructure and resulting amount and sign of residual stresses. An increase of compressive residual stress and decrease roughness can heighten fatigue life.

(2) There are many defects on machined surface produced by DBM, DBK with dry cutting, which arouse large roughness, high cutting temperature, strong plastic deformation and low fatigue resistance. In contrast, Winslow with lubrication has better surface quality, such as plat smooth surface, high compressive residual stress and strong fatigue resistance.

(3) Under the existing multi-step drilling processes, there are poor surface quality, which can not prevent fatigue damage development. It is need to improve processes, that is appropriate increase in cutting speed and decrease in feed rate.

(4) Winslow can increase the fatigue life, cut down dispersion and improve required surface properties of fastener holes. Therefore, it is an efficient, fast and high-quality drilling process and can be employed widely in aircraft assembly.

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