Lightweight tooling for concentric collet drilling templates

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Abstract. This paper aims to meet clear business demand for lighter operational jigs and tools by reducing the overall weight of the concentric collet drilling templates using alternative lightweight materials and topology optimization techniques. The template structure was optimized by numerical modelling to reduce the mass and maintain relative strength. A cycle test that simulates the actual working conditions of the templates was conducted to understand the deformation and wearing during and after their usage. The simulation results indicate the challenges between reducing the mass and maintaining the stiffness of the drilling template. The hole size in each alternative aluminum template increased after 10,000 times of cycle tests; For harder materials like Al7075, the hardness of the borehole increased due to its high strength to resist extending force from the collet. Whereas, for the materials with lower hardness like Al5083, the borehole hardness reduced after the cycle tests due to its low strength. The borehole surface roughness in the template increased due to wear caused by the horizontal pressure and vertical contact by the collet, which would severely increase the friction and reduce the lifetime of the template.

Keywords: Drill jig template; Aluminum hardness; Friction and wearing damage.

1 Introduction

A jig is a type of tool used to control the location and/or motion of another tool. It is a work-holding device that holds, supports, and locates the workpiece and guides the cutting tool for a specific operation [1]. The primary purpose of a jig is to provide repeatability, accuracy, and interchangeability in the manufacturing of products [2]. Drilling jigs such as those used in creating holes in aerospace structures provide methods for correctly locating the workpiece with respect to the cutting tool [3]. Compared to conventional hand methods drill jig helps in drilling, reaming, and tapping holes at a higher speed with great accuracy [4]. Millions of holes are drilled (single or multi-stage operations) into aircraft structures and the positioning of the drill is provided by drilling templates. These templates, manufactured mainly from wrought 7075 Aluminum machined plates, have proven effective over time. However, there is also a lack of knowledge regarding how long a drill jig lasts and its accuracy over the lifetime which is important information. As the demand of the aerospace industry for high-performance tooling is increasing, the use of lightweight tooling that would result in a reduction of the handling time, number of operators, and lower risk of injuries potentially provide a good market opportunity to introduce new materials/manufacturing technologies into the tooling making process and market.

The structure optimization of drilling jigs was investigated mainly via modelling simulations or Computer-Aided Design (CAD) due to the low cost and fast [5, 6, and 7]. Material is the other factor of research on jigs. They are products of hardened material to avoid frequent injury and to resist wear. the fabric used for jigs and fixtures are soft-cast steel, cast iron, die steel, steel, high speed steel, nickel-chrome steel, bronze, plastic material etc. [8, 9, and 10].

The objective of this paper is to reduce the overall weight of the concentric collet drilling templates by using alternative lightweight materials and topology optimization techniques. Two aspects were considered, including optimizing the structure of the templates by reducing the volume and applying lighter materials. Numerical modelling was used to optimize the template structure for reducing the mass and maintaining relative strength. The cycle tests of simulating the actual practice were carried out on the alternative templates to understand the deformation and wear behavior during and after their usage.

2 Modelling and Experimentation

2.1 Modelling

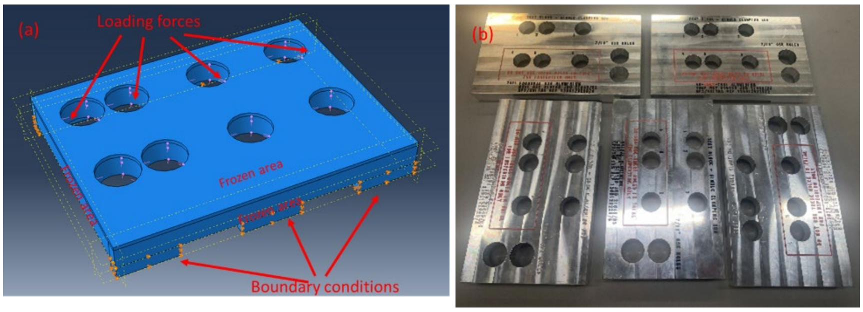


Fig. 1. The modelling of the templates (a) and alternative Aluminum templates (b).

To achieve a better understanding of the response of the hole dimension change on the existing drilling templates against various loading conditions, Finite Element Analysis (FEA) modelling was carried out for simulation. Al7075 was used as the raw material for the modelling. The loading force was 5000 N on each hole and the mass reduction was 30% off, 40% off, and 50% off, respectively. Boundary conditions that all the legs were fixed were also applied to the modelling as shown in Fig. 1(a).

2.2 Template Design and Materials

Table 1. Average hole diameters on each template by CMM (mm).

Al7075 (B1)		Al7072 (B2)		Al6082 (B3)	
B1-1	B1-2	B2-1	B2-2	B3-1	B3-2
35.020	35.021	35.025	35.022	35.010	35.011

Al5083 (B4)		Unidal Al (B5)	
B4-1	B4-2	B5-1	B5-2
35.015	35.014	35.011	35.009

It was considered more benefits could be derived by replacing a high-cost Aluminum 7075 with a cheaper and easier Aluminum material. Therefore, the templates of 5 different Aluminum materials in the tests were shown in Fig. 1(b), including Al7075(the current material of used templates), Al7021, Al6082, Al5083, Unidal Al. Two adjacent holes on each template were measured as candidates for the tests as shown in Table 1. All hole diameters were under H8 tolerance (0-0.039 mm) which is technically required. The thickness of all templates was 20 mm.

2.3 The Machine Design, Cycle Tests, and Measurements

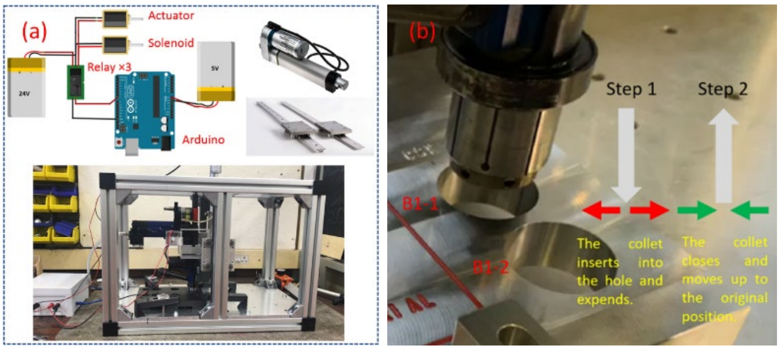


Fig. 2. Cycle test hardware and mechanism, (a) automatic hole expansion testing rig with actuator and guide rail, (b) the schematic.

To simulate the actual working conditions of the drilling hole by the guidance of the drilling jigs, the cycle tests were conducted on the templates. The cycle test is that, specifically, the Advanced Drilling Unit (ADU) will insert the drilling jig and the collet will expand to be fixed by the jig holes and then the drilling conducts (will not apply drilling in the tests). After a while of extending (5 s in this test), the collet closed and then ADU move up to the original position. A test rig was developed to control the ADU movement and operation of the ADU simultaneously and fully automatically, as presented in Fig. 2 (a). An actuator which controls the movement of the ADU in the z-direction was connected to the ADU. Two relays were added to the system which allows the control of the extension and retraction of the actuator. A solenoid was used to switch on/off the expansion of the ADU which was activated by the air pressure of 5 bar. An Aluminum frame was built to house all the controlling components and two guide rails were installed to stabilize the movement of the ADU. By adjusting the cycle frequency and ADU dwelling time, this automatic hole expansion testing rig is capable of repeating thousands of testing cycles within hours. The cycle test schematic was shown in Fig. 2 (b).

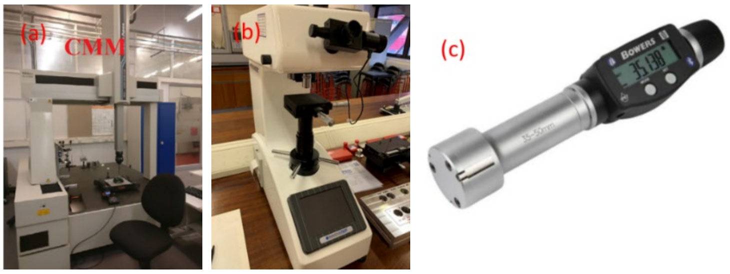


Fig. 3. Measurement devices, (a) the coordinate measuring machine (CMM), (b) the hardness tester, and (c) the bore micrometer for intermittent measurement.

During the testing process, the ADU was controlled with a frequency of 5s open and 5s closed, and between each cycle, the ADU would lift from the hole and go down into the hole again to simulate the drilling cycles. According to measurement, the collet diameter is approximately 34.93 mm when being closed and approximately 35.27 mm when extending. For tests on alternative Al alloy, 10,000 cycles were repeated on each tested hole. Intermittent measurements were completed at 1000, 3000, and 6000 cycles for analyzing the transformation during cycle tests. Fig. 3 shows the device to measure hardness and the size of the holes before and after the cycle tests to understand the impacts of cycle tests on the templates.

3 Results and Discussion

3.1 Numerical Modelling

Topology optimization was conducted to reduce the weight of the concentric templates by 30%-50%. Several topology optimized models were developed as shown in Fig. 4. Some examples of Al7075 were given below showing the topology optimization process undertaken to maximize the stiffness/weight ratio with different weight reduction rates for template CAD models.

Based on the simulation results shown in Fig. 5, some conclusions can be made that with the reduction of mass percentage, the maximum displacement would increase. In addition, the optimized design will differ when applying different additional loading and boundary conditions, which depends on the specific requirement of each template during the manufacturing or handling process.

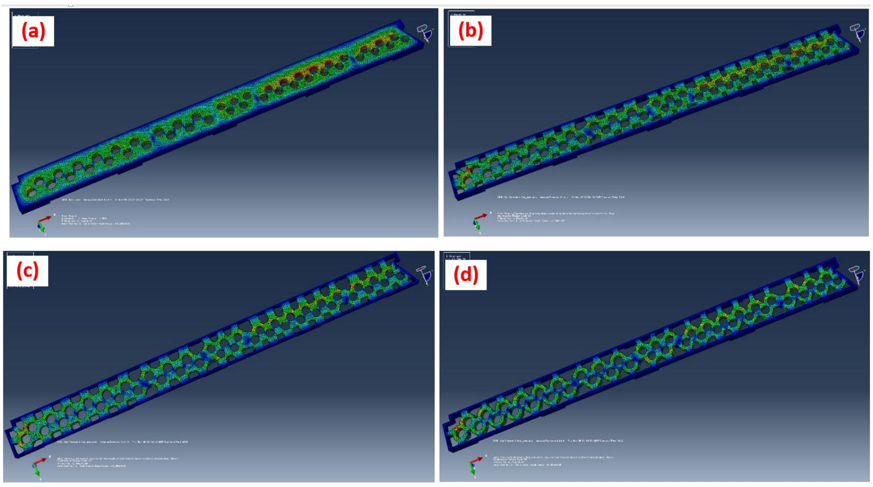


Fig. 4. Topology optimized template of Al7075 with (a) 0%, (b) 30%, (c) 40% and (d) 50% weight reduction.

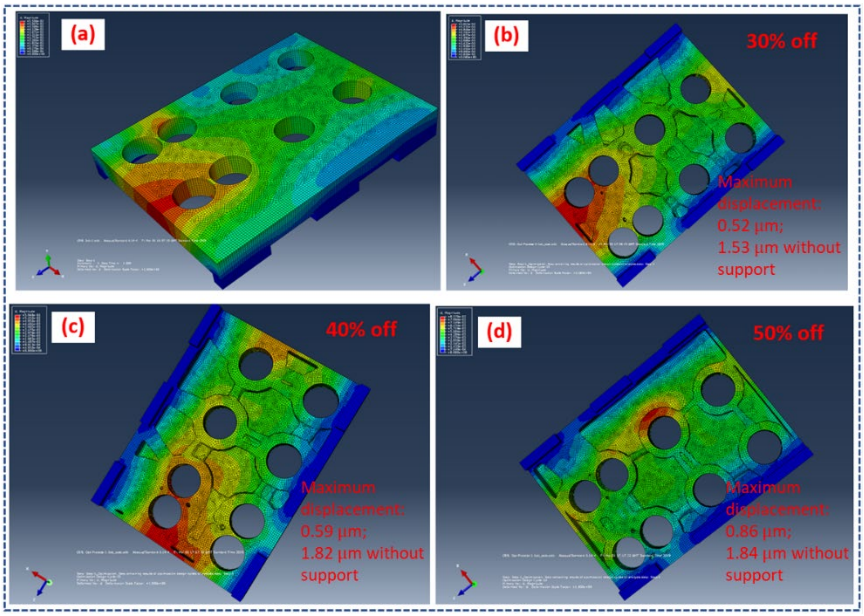
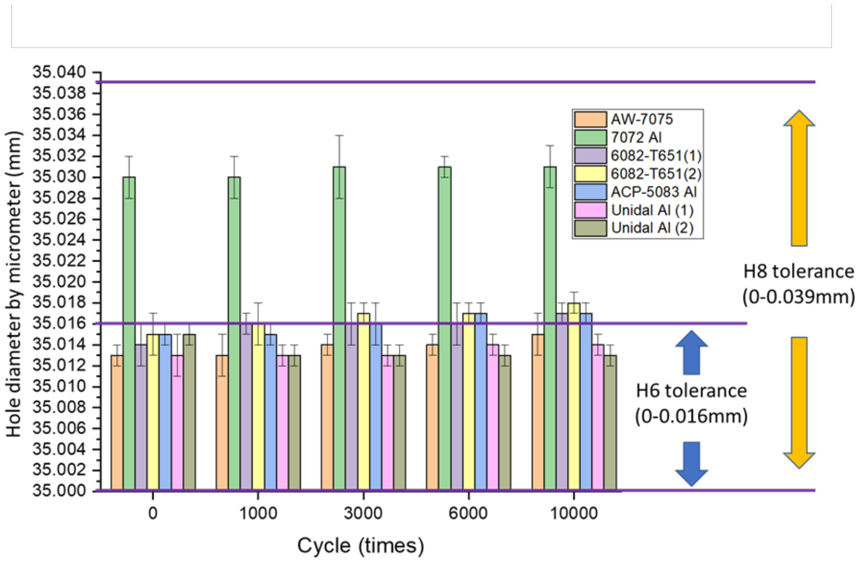


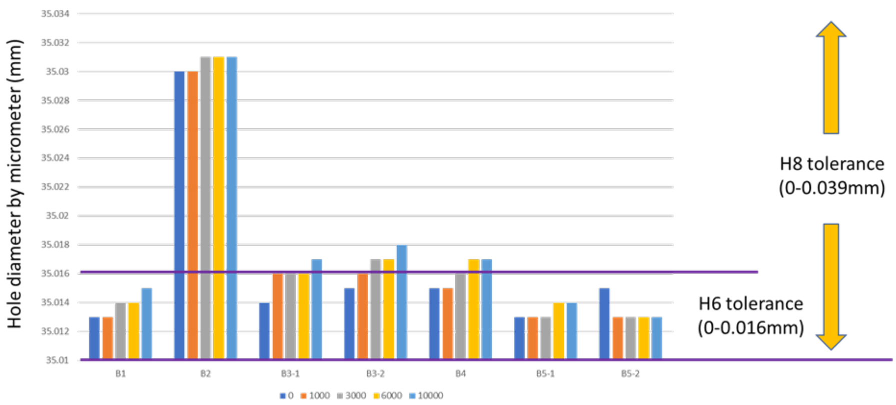
Fig. 5. Topology optimization of the modified template of Al7075 with different weight reduction.

It can also be noticed from the modelling results that even after applying additional loading conditions, the maximum displacement is still quite low (less than 5 µm), indicating that the reduction in template mass would not have a major impact on the dimensional response of the template, since it is still within the elastic deformation range.

3.2 Cycle Test Results of Alternative Aluminum Templates



(a) Results of the hole diameters by the micrometer from 0 to 10,000 times of cycle tests.



(b) The diameter changes for each material during cycle tests.

Fig. 6. The cycle test results of each hole.

The final diameter after cycle tests were measured by both bore micrometer and CMM machine. Cycle tests were done on one hole of Al7075 (B1), Al7072 (B2), Al5083 (B4), and Unidal Al (B5); on both holes of Al6082 (B3) (for comparison of insertion/extraction cycles and non-insertion cycles). The other hole that is adjacent to the tested one of Unidal Al was also measured for understanding the impact on the non-cycled hole.

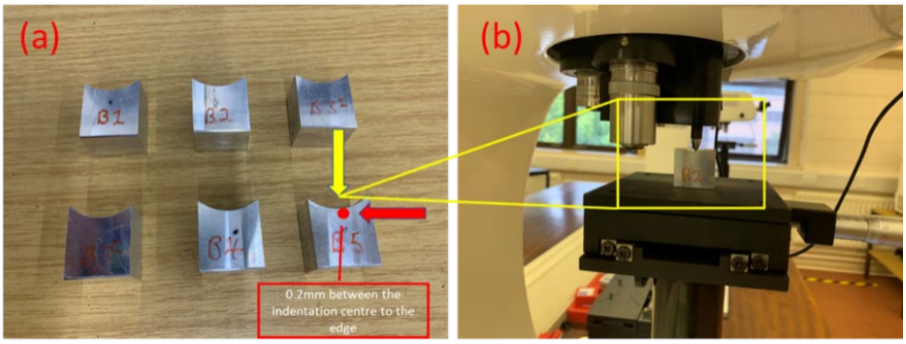
Fig. 6 shows the results of all diameters after cycle tests measured by the micrometer. From the figure, the Al7021 had a much bigger diameter than others due to manufacturing issues. The diameter increased gradually during cycle tests due to both horizontal extending force and vertical friction. From Table 2, the deformation rate of each hole was calculated, which is for understand the relationship between the deformation and hardness. The hole diameter increased after cycle tests. The increasing rate was much higher if the hardness of the material is low. For harder materials, for example, Al7075, the increasing rate was low. It can be seen the Al6082 and Al5083 have relatively low hardness and their increasing rate are relatively high. The shrinkage rate of the non-tested hole (Unidal Al - 2) is much higher than the increasing rate of the tested hole (Unidal Al - 1) even though there is a 5mm-thick wall between the two holes.

Table 2. The deformation rate of each hole after 10,000 cycle tests ("+" presents extending and "–" presents shrinkage of the hole size).

Materials	Al7075	Al7021	Al6082-1	Al6082-2
Hardness (HV)	182.3	125.4	113.8	113.8
Increasing rate	+0.0057%	0.0%	+0.0086%	+0.0086%

Materials	Al5083	Unidal Al-1	Unidal Al-2
Hardness (HV)	85.0	139.9	139.9
Increasing rate	+0.0057%	+0.0029%	-0.0086%

Hardness tests were conducted on the edge and the wall of each tested hole respectively (shown in Fig. 7), to understand how the material was hardened by the cycle tests. Results were shown below in Figure 8. The indentation loading was 5 kg with Vickers indenter. The distance between the central point of the indentation and the edge is about 0.2 mm.

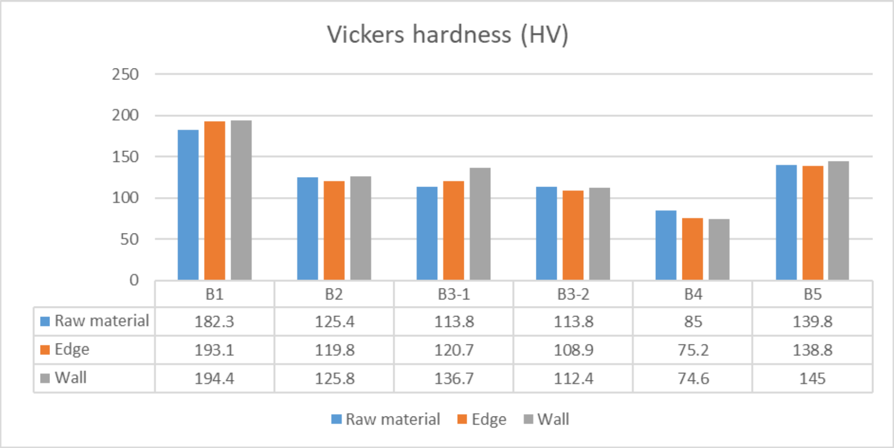


0.2mm between the indentation centre to the edge

Fig. 7. Hardness tests on the edge and the wall of the hole.

For hardness tests on the edge, as the indentation was closed to the edge, some materials were pushed down due to the plastic deformation, therefore, the size of the indentation would be larger than normal, which led to lower results than normal. Therefore, the tested results shown in the table and figure can only be used for information rather than accurate results.

For the hardness of the sidewall, it can be seen from the figure above that for the materials with relatively higher hardness, for example, Al 7075 (B1) and Unidal Al (B5), the hardness results of the sidewall were higher than the raw materials. For the materials of medium hardness like Al 7021 (B2) and Al 6082 (B3-2), the hardness of the sidewall did not have major differences from the raw materials. The result of Al 6082 (B3-1) was much higher than the raw material because severe wearing due to the friction during cycle tests happened, which has led to much higher hardness. For the relatively softer material, Al 5083 (B4), the result was even lower than the raw material.



	B1	B2	B3-1	B3-2	B4	B5
Raw material	182.3	125.4	113.8	113.8	85	139.8
Edge	193.1	119.8	120.7	108.9	75.2	138.8
Wall	194.4	125.8	136.7	112.4	74.6	145

Fig. 8. Vickers hardness results

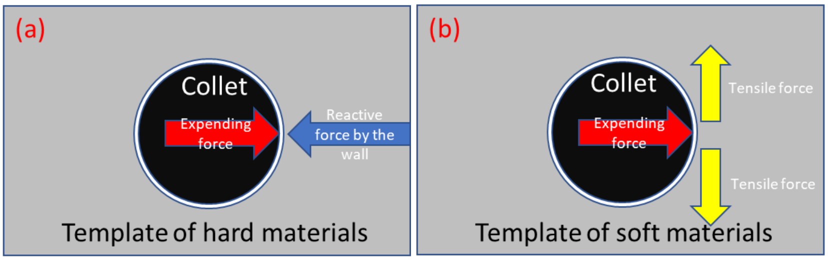


Fig. 9. The schematic of forces from the collet extending to different materials, (a) for hard materials and (b) for soft materials.

For the harder materials, for example, the Al7075, when the extending force worked at the sidewall, the solid material would resist the force and the sidewall was compressed due to its relatively high strength as shown in Figure 9 (a). The material of the sidewall was hardened by the pressure; therefore, the density and the hardness would increase.

Compared with the hard materials, when the extending force acted on the sidewall of Al5083, the material is not able to resist the force due to its lower strength as shown in Figure 9 (b), which became the tensile force to the sidewall. Due to the tensile stress, the density of the sidewall would reduce, and the hardness goes down as well. In this case, the deformation is still in elastic range, which can also be proven by the simulation results of low-strength materials/structures in section 3.1.

For the materials of medium hardness, the sidewall is both compressed and stretched from the extending force of the collet. Therefore, the hardness of the sidewall did not have a big change after the cycle tests.

3.3 Damage due to Friction and Wearing

During cycle tests, it was found that inserting and extracting the collet will increase wearing between the hole wall and the collet. Specifically, when the collet opens, it has both vertical displacement and horizontal extension. The vertical displacement will lead to friction which can be increased by horizontal extension as shown in Figure 10 (a). This friction will severely damage the wall quality and impact the circularity as shown in Figure 10 (b). This effect has more influence on the hole size than the extending transformation by horizontal extending force. Therefore, wearing tests to understand the tribological properties of the material is worth considering, which is significant for optimizing the cycle test parameter and choosing the appropriate material for the practical drilling tasks.

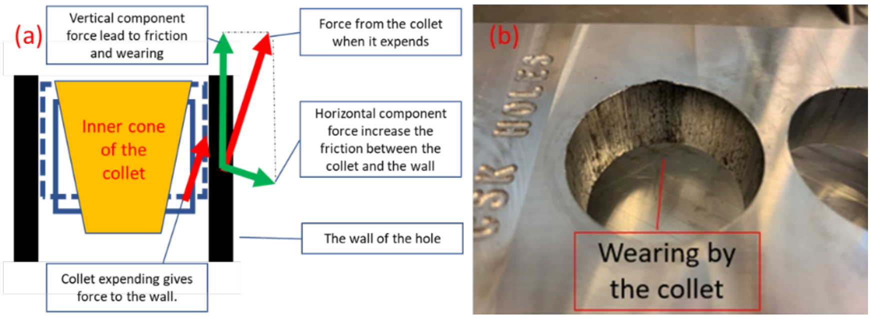


Fig. 10. (a) Analysis of the friction between the collet and the hole, (b) demonstration of wearing of the jig.

Conclusions

In this paper, the structures of the templates were optimized by numerical modelling. The simulation results indicate the challenges between reducing the mass and increasing the strength. The alternative lightweight materials and topology optimization techniques can effectively reduce the overall weight of the templates while keeping the performance. Five alternative Aluminum materials were tested. The diameter of the hole increased after cycle tests; however, all increased diameters were under H8 tolerance after 10,000 times of the cycle test. For the materials with higher hardness like Al 7075, the hardness of the sidewall of the hole increased due to its high strength to resist extending force from the collet. Whereas, for the materials with lower hardness like Al5083, the hardness of the wall reduced after the cycle tests due to its low strength. Wearing from the horizontal pressure and vertical friction between the collet and the hole damaged the surface of the hole, resulting in a rough surface, which would severely increase the friction and reduces the lifetime of the templates. By the modelling and experiments in this paper, the mass can be significantly reduced as well as the cost of the materials as the current Al7075 can be replaced by Al5083 with lower hardness and price while keeping relative decent performance during the tests. The cycle test that simulates the actual working conditions of drilling jigs can be also applied to similar tooling to identify any potential possibility to improve the performance and reduce the cost.

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