Mechanical Joining Methods for Additive Manufactured Assembly Tools

Anthony Pimentel, Tiago Noversa, Luis Freitas, J. P. Nunes & António Brito
Institute for Polymers and Composites IPC/I3N, University of Minho, Guimarães, Portugal

Ricardo Lima & Tiago Alves
Bosch Car Multimedia Portugal, S.A., Lomar, Braga, Portugal

ABSTRACT: The use of additive manufacturing (AM) processes is growing in the manufacturing industry. One application with great potential for using these processes is the manufacture of assembly tools for a highly competitive markets, such as the automotive industry.

A critical aspect of the assembly tool design is its capability to incorporate modifications even at a late stage of its development in very short time. In many cases, these modifications are achieved using metal inserts in the polymeric tool, which allow to add new geometric features. This capability increases the usefulness and versatility of components produced by AM and compensate for potential shortcomings of using additive materials. The purpose of this paper is to evaluate the potential use of accessories in additive manufactured components. In addition, the effect of different percentages of infill tool material on the joining quality of accessories is evaluated. This is done by performing a screw pull-out test on a ABS ESD-7 part, produced by fused deposition modelling. The following different joining solutions were compared and studied in this work: embedded inserts, glue, heating processes, pressure (Tap-in) and creation of threads, such as, printing the thread directly and machining the thread onto the material.

1 INTRODUCTION

1.1 *Background*

Currently, to design and develop new products a closer relationship between the designer team, responsible for production and other sectors downstream to the production cycle is required. This concept is known as “Concurrent Engineering” and allows to minimize the development time, reduce costs, increase quality and performance of delivery. As an example, it is estimated that the costs associated to product alterations design or functionality, when the product is already on the production and commercialization phases, could be reduced about 100 times if product design was corrected in the prototyping and testing phases (Dieter & Schmidt, 2000). From this point of view, the rapid and easy production of prototypes have a key role in the industrial world. In a broad sense of term, the rapid prototyping (RP) encompasses a set of physic modeling technologies to produce models and prototypes quickly from the 3D model’s information (Kochan, 1993). Such prototypes can be produced by additive manufacturing (AM) or subtractive manufacturing (SM) technologies. The AM consists in the production of a product by using techniques of deposition of successive material layers (ASTM International, 2012). AM is ideally suited for RP, since it allows the rapid creation of complex geometries with minimal material waste and a better cost competitiveness than SM.

Application of the RP principles to industrial processes in a consistently and robust way, accompanying the entire production cycle is defined as Rapid Manufacturing (RM). At this level, the RP techniques, in which AM is included, are not used to manufacture prototypes, but mainly for large series production (Pham & Gault, 1998). Later, the concept of rapid tooling (RT) emerges and consists in applying the RP principles to the production of tools (Levy, Schindel, et al. 2003). All these concepts are exposed in Figure 1.

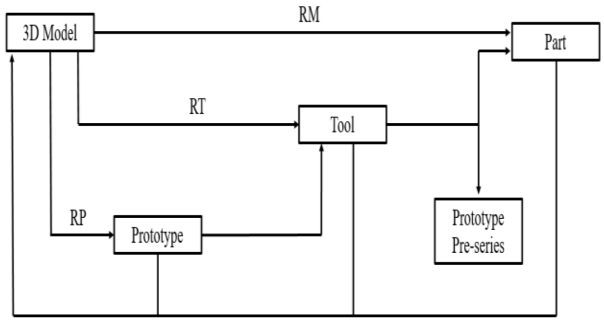


Figure 1. Rapid Prototyping (RP), Rapid Manufacturing (RM) and Rapid Tooling (RT).

Throughout this study, the focus will be on the use of AM techniques in the rapid construction of feasible assembly tools. The production of tools using Additive Manufacturing brings advantages such as the production of complex geometries that would not be possible through other means, without resulting in increased lead time for production. Furthermore, a significant reduction in mass due to use of polymeric materials, comparing with metallic tools made from subtractive manufacturing, is still achieved. (StrataSYS, D.M., 2016) (Bandypadhyay, & Bose, 2016)

1.2 *Additive Manufacturing and Assembly Tools Requirements*

A recent study made in the RT field of is related with the construction of assembly devices (JIGS). The jigs are used to support and guarantee positioning products in a unique (*poka-yoke*), accurate, repeatable and automatic way that allows assembly tasks being performed accordingly a predefined sequence and using specified control parameters (Kakish, Zhang, & Zeid, 2000). An assembly device must necessarily guarantee the dimensional and geometric tolerances that are required to allow the correct positioning of the components to be assembled.

One of the most used techniques is the Fused Deposition Molding (FDM), which consists of a movable head that deposits material on a substrate in order to build the final desired object layer by layer (Wong, & Hernadez, 2012). One of the great advantages of this technique is that it allows the construction of solid parts and *sparse* parts, i.e. parts that are produced with only a certain percentage of the infill material. The *sparse* parts are made with an internal mesh that can be adapted and optimized according to the final function performed by the part to be produced. The different shapes of mesh offer several different levels of strength and stiffness. Some meshes that can be used inside of parts are shown in Figure 2.

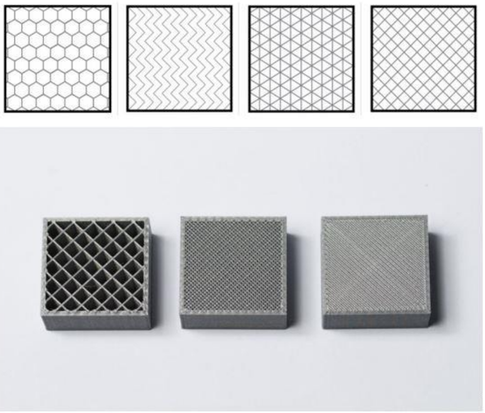


Figure 2. Different mesh geometries for the inside of the parts.

In an assembly device, weight reduction facilitates the transport and handing of tools, mainly in changeover operations (StrataSYS, 2016). Thus, the fact that jigs can be made by using AM, namely the FDM technique, provides economic advantages and improves the usability of these devices.

In the electronics component industry, it is necessary to ensure that materials used in the assembly devices present adequate Electronic Static Discharge (ESD) characteristics. One of the possible ESD materials that may be processed by FDM technology is ABS-ESD7.

The dimensional requirements of an assembly process are dependent from the sum of the manufacturing tolerances of each component with those of the jig fabrication process. Thus, the smaller the tolerances of the final product the higher will be the dimensional requirements for the tools and jigs mounted on its assembly device (Bhosale, Nalawade, et al., 2017). In recent years, the quality requirements in the automotive sector have increased significantly, this has triggered the need for large investments to control the quality of assembly processes and ensure much tighter tolerances (Inman, Huang, et al., 2010).

In the industrial practice, the assembly tools design includes some gap adjustment systems, within a certain tolerance range, to compensate some potential lack of process robustness. Additionally, the assembly processes and tools design must be flexible enough to incorporate product changes in a very short time, sometimes made during at a late stage of the tools development due to the design freeze phase being increasingly reduced. In many cases it is necessary to redefine new locating holes or fix new components in the polymeric tools. To increase the tools flexibility and perform the necessary modifications it is common to use metal accessories, which also allows to connect other metal components in areas of wear to increase the tool life (Eger, Eckert, & Clarkson, 2005).

Therefore, the implementation of accessories is essential to ensure the optimal design of an assembly tool. These accessories will allow the use of pins, threads and bushings, giving the tool the ability to fulfil all design and dimensional specifications. Such accessories are usually coupled with additive manufactured tool by using some of the following ways that may be found in technical literature:

- Using glue;
- Through the process of heating;
- With pressure (Tap-in).

For making threads, the following ways are very often used to build the threaded connection in FDM technology:

- Subtractive manufacturing;
- Printing the thread directly.

All the pointed solutions for connecting accessories and building threads have their own advantages and disadvantages. However, it is still difficult to find well-sustained studies and the information needed to establish good design rules for coupling accessories and manufacturing threads on AM tools to be used on assembly devices. This study presents a simple experimental methodology to assess and compare different fixing solutions through the determination of the pullout strength of a screw. The outcomes will identify which method of coupling is more robust and which should be used in solid and *sparse* tools produced by additive manufacturing, namely, by using the FDM technique and an ABS-ESD7.

2 EXPERIMENTAL TESTS

2.1 *Methodology*

Using the different solutions mentioned in the previous section, a screw was fixed to an ABS-ESD7 part manufactured by a FDM to be pulled in a 5kN *Zwick Roell Z005* universal testing equipment by using a crosshead speed of 10 mm/s. The maxima pull-out forces reached were record from the three tensile tests made for each studied solution, for comparison between the different methods under investigation.

For the gluing process, the glue was applied on the outer area of the insert, it was then fixed on the part hole. The glue used was an ethyl cyanoacrylate, which was let to dry during 24h.

For the heated process, the insert was heated until 410ºC and then pressed on top of the part hole, until it was fully inserted.

Since the diameter of the initial holes for the different solutions will affect the test results, it was decided that two different parts will be manufactured. One for M3 threads/3mm holes and other for M6 threads/6mm holes. Also, one full and another sparse infill part will be produced for each test part.

The percentage of the sparse to be used was another important factor taken into account. In the present work it was chosen the value recommended by the manufacturer of machine used to produce the FDM part in ABS-ESD7: 50% of infill material. The percent unfilled parts were produced with holes having wall thickness of 1 mm and 10 mm [Figure 3].

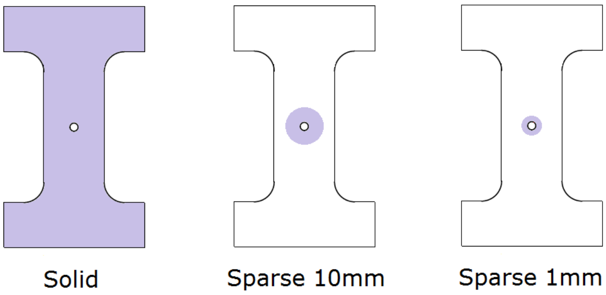
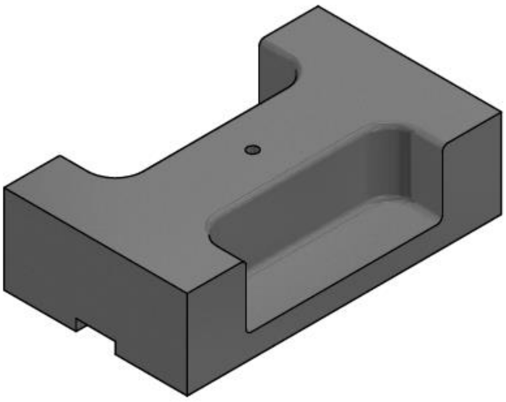


Figure 3. Mesh configurations and hole wall thickness.

The mesh configurations presented (Solid, Sparse 10mm and Sparse 1 mm) were used for each type of joining process.

2.2 *Test Parts and Machines*

The test part used in the experiments and its dimensions are presented in Figure 4. The part was designed in order to use the minimum amount of material needed for the envisaged purpose without compromising its robustness. The part was produced by using a FDM *Stratasys Fortus 900mc* equipment and an ABS-ESD7 as material.



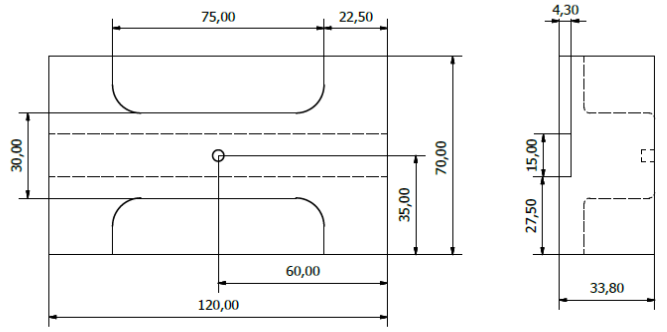


Figure 4. 3D representation of the Test Part and 2D drawing.

To perform the pull-out tests, a custom-made clamp device [Figure 5] was designed to fix the part to be tested to the universal testing machine to ensure that it is held in the proper place during the execution of the test.

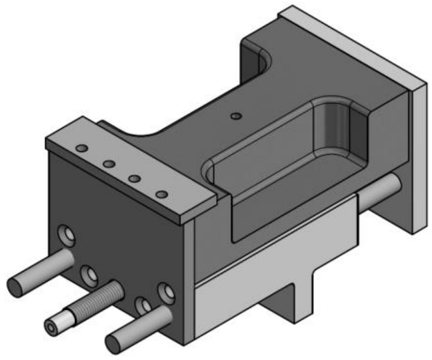


Figure 5. Test part fitted into the custom-made clamp.

The clamp and part set were then placed and fixed in the universal machine for the execution of the test [Figure 6].

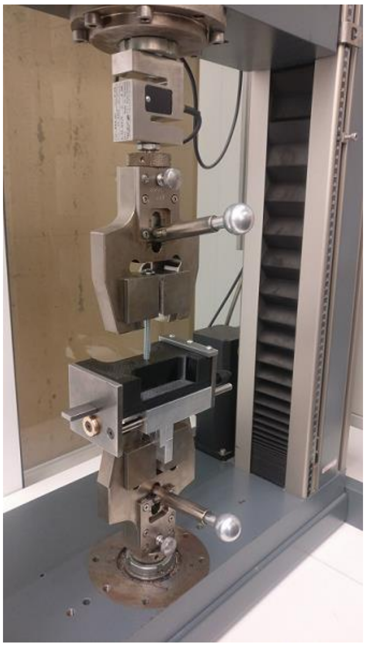


Figure 6. Test part and custom-made clamp assembly fitted onto the universal testing machine.

3 EXPERIMENTAL RESULTS

Figure 7 shows the average pullout force curve profiles obtained from the different tests made on the solid M3 parts.

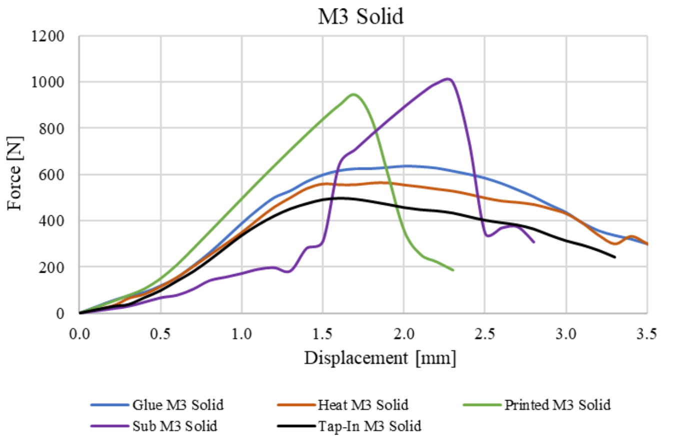


Figure 7. Average pullout force curve profile for solid M3 parts

Maximum average values of 1 kN and 0.94 kN were obtained for tear forces from the tests made with machined and printed threaded connections, respectively. Depending on the joining method, the ones using the metallic insert reached maximum load between 50% and 65% of those obtained in the tests performed with threaded joints. Furthermore, an abrupt decrease of the pullout force may be observed after the maximum values have been reached in the tests made with threaded joints, while this did not happen in the joints tested with metallic inserts.

Figure 8 shows the average pullout force curve profile obtained from the 10mm sparse M3 parts.

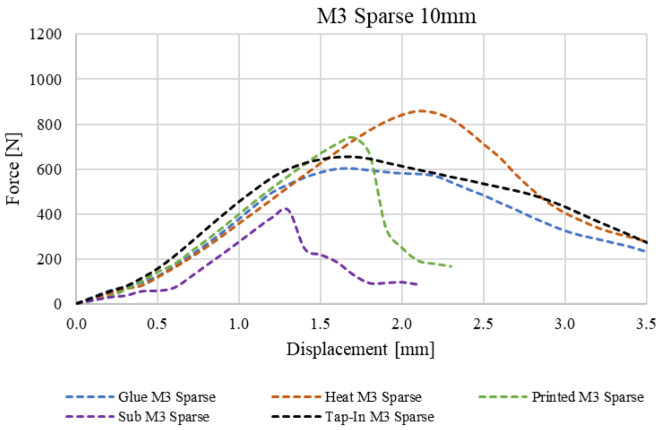


Figure 8. Average pullout force curve profile for 10mm sparse M3 parts

The average pullout force curve profiles for 10 mm thick parts indicated the same kind of behavior for the threaded solid parts and inserted joints. Specifically, an abrupt drop after reaching maximum value in pullout force may be seen for the threaded joints and a much smoother drop in the joints using inserts.

As opposed to de solid M3 parts, the 10mm sparse M3 parts that withstand the most average pullout force, equivalent to 0.86 kN, were the heat metallic inserted. On the other hand, the smallest average pullout force value was withstood by the machined threaded joints, with a, lower than expected, value of 0.42 kN. The printed thread endured a load of 0.74 kN, whilst the tap-in and glued joints achieved, respectively, 0.65 kN and 0.60 kN.

Figure 9 shows the average pullout force curves obtained from the 1mm sparse M3 parts.

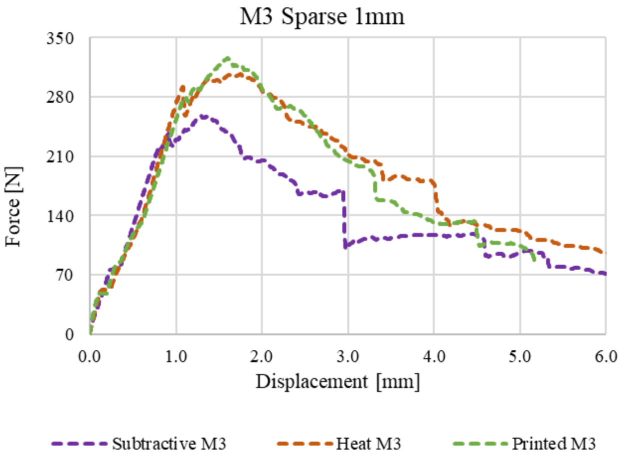


Figure 9. Average pullout force curve profile for 1mm sparse M3 parts

The M3 1mm sparse parts average pullout force achieved a maximum value of 0.32 kN for the printed thread parts, and a minimum value of 0.25 kN for the machined thread parts. The heated metallic inserts parts reached average pullout force very close to printed thread parts.

Figure 10 shows the average pullout force curve profile obtained from the solid M6 parts.

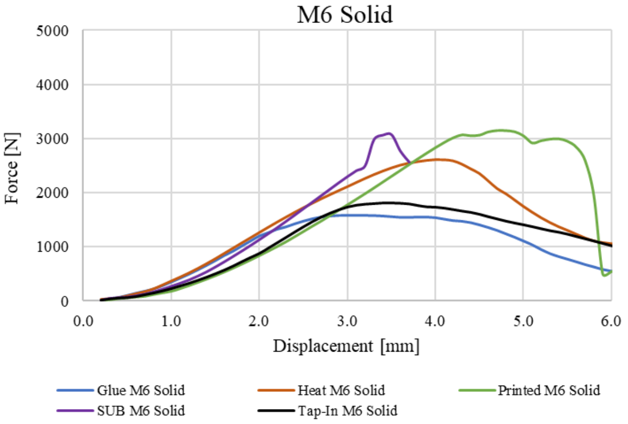


Figure 10. Average pullout force curve profile for solid M6 parts

Maximum pullout force around 3.1 kN were achieved for M6 solid parts threaded joints. Just below, the heated metallic inserts presented a maximum average pullout force of 2.60 kN. The tap-in and glue joining methods reached maximum pullout force of 1.80 kN and 1.50 kN, respectively.

Figure 11 shows the average pullout force curves obtained from the 10mm sparse M6 parts.

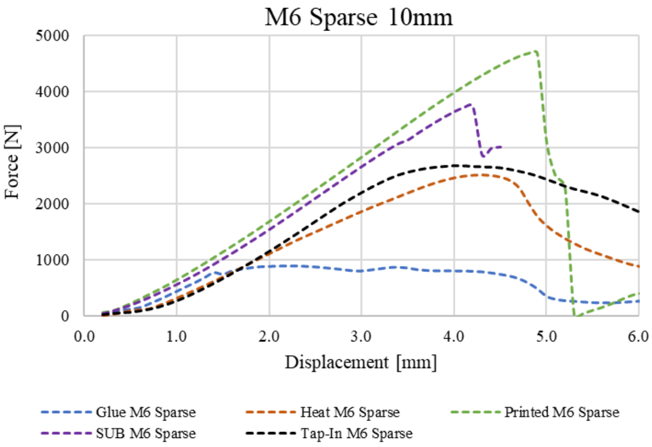


Figure 11. Average pullout force curve profile for 10mm sparse M6 parts

The results for the 10mm sparse M6 parts, reproduce the behavior already observed for the M3 parts. The threaded joints were the most resistant and presented the most abrupt reduction of force after achieving the maximum pullout force. The metallic inserts were the least resistant and presented a smooth reduction of force after maximum value is been achieved. The maximum pullout force obtained are 4.70 kN and 3.70 kN for printed threads and machined threads, respectively. The tap-in and heated achieved, respectively, values of 2.68 kN and 2.52 kN of maximum pullout force. However, the glued inserts did not withstood more than 0.90 kN.

Finally, Figure 12 shows the average pullout force curves obtained from the 1mm sparse M6 parts.

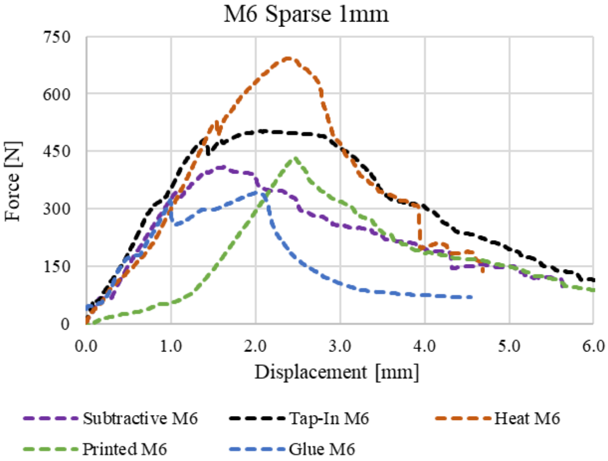


Figure 12. Average pullout force curve profile for 1mm sparse M6 parts

For the 1mm sparse M6 parts the maximum pullout force value where very close to 0.70 kN, achieved by the heated metallic inserts. On the other hand, the lowest pullout force (0.34 kN) was achieved by the glued inserts. The maximum pullout force value obtain for tap-in inserts was of 0.50 kN. Regarding the threaded joint parts, the maximum supported load value was 0.43 kN for printed threads and 0.40 kN for machined threads.

4 DISCUSSION OF RESULTS

Screw threaded joints normally presented a higher strength to pullout forces when compared to joints obtained through metallic inserts. Additionally, it was expected similar strength for both cases (machined and printed). However, these values may have a slight difference since, the robustness of the joint depends exclusively on the quality of the thread, as it is suggested by the results shown in Table 1 and 2 for the M3 and M6 threads, respectively.

Table 1. Maximum pullout forces obtained in the tests for the M3 threaded joints.

M3	**Solid Force (N)**	**Sparse 10mm Force (N)**	**Sparse 1mm Force (N)**
Machined Thread	1000	420	250
Printed Thread	944	740	320

Table 2. Maximum pullout forces obtained in the tests for the M6 threaded joints.

M6	**Solid Force (N)**	**Sparse 10mm Force (N)**	**Sparse 1mm Force (N)**
Machined Thread	3067	3735	402
Printed Thread	3145	4690	430

The quality of threads on a hard-polymeric material, like the ABS ESD-7, is not easily accomplished. Thus, some variability of aspect was well observed in the manufactured threads, particularly those having smaller size (M3). Although the quality of the printed threads seemed to be worse than of the machine threaded ones, they had withstood superior loads. In the poor quality printed threads, this happened probably because, in this case, the screw was forced to deform the material during the screwing, producing a “thread” totally adapted to its shape. Therefore, the printed thread ultimately achieves a more rigid joint than the machined thread (see Table 1 and 2).

However, due to the differences and lack of consistency observed in the experimental data obtained it is difficult to draw definitive conclusions about the performance of all different joining solutions that were tested. Comparing the maximum average values of the pullout forces for the threaded joints (machined and printed), it may be concluded that the forces needed to break the joint do not differ too much between the solid and 10mm sparse parts.

Looking, for example, to the M6 thread results (see Table 2) the higher average force were obtained for the 10 mm sparse parts, which always failed (yielding) by the thread. Therefore, it may be concluded that the 10mm sparse parts are clearly accomplish enough performance to replace the solid parts as joining solution due to the material savings it allows to achieve. However, some improvement may be obtained by carrying out work on increasing the robustness and quality of the thread. The higher unexpected average pullout force obtained in the case of printed thread of M6 10mm sparse part, seems to result from deeper screwing that was possible to make in this case (Table 2)

Comparing the M3 10 mm sparse and solid parts, it may be concluded that the lack of quality of the machined thread led to a decrease of the maximum pullout forces for the M3 10 mm sparse part(see Table 1).Figure 13 takes into account the results in Table 1 and Table 2 and presents the average pullout forces for M3 and M6 threaded joints.

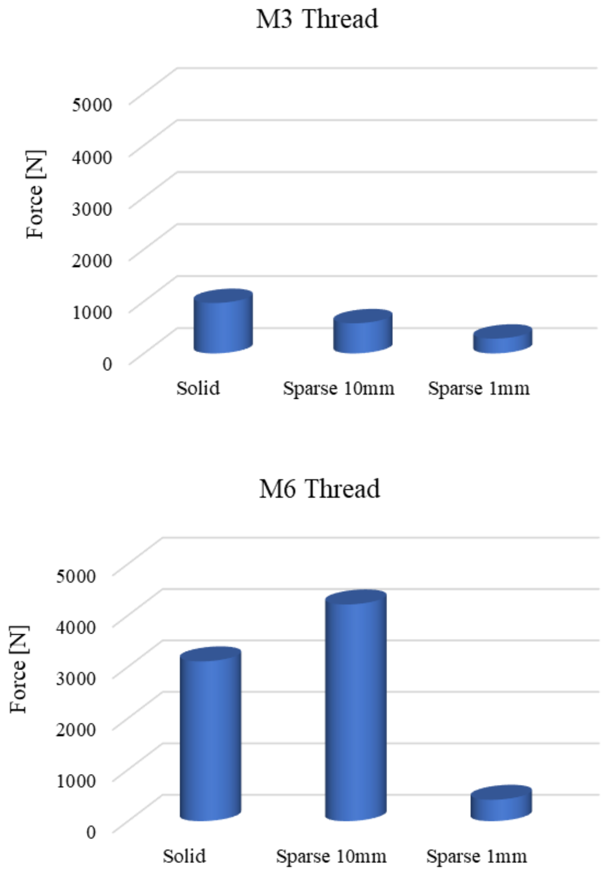


Figure 13. Average pullout force for M3 and M6 threaded joints of all mesh configurations.

For the threaded joints, the use of minimum thickness causes the pullout force to fall abruptly because the joining strength becomes only dependent of the small mesh strength, which fails before the thread. Changing, for example, from a M3 thread to a M6 thread leads to a 1.5 time increase in the average pullout force. Nevertheless, the increase on the average pullout force is 3 and 7 times bigger for the solid and 10mm sparse parts, respectively, than the 1 mm sparse ones. If the thread manufacturing and the screwing process were optimised, it is possible that the maximum average pullout force for the solid and 10mm sparse cases could converge for a value approximately 5 times bigger than the one obtained for the 1 mm sparse part.

Table 3 and 4 present the maximum average pullout forces obtained for the inserted joints.

Table 3. Maximum pullout forces obtained for the M3 metallic insert joints.

M3	Solid Force (N)	Sparse 10mm Force (N)	Sparse 1mm Force (N)
Glue Joint	635	600	---
Heat Joint	565	856	305
Tap-In Joint	498	653	---

Table 4. Maximum pullout forces obtained for the M6 metallic insert joints.

M6	Solid Force (N)	Sparse 10mm Force (N)	Sparse 1mm Force (N)
Glue Joint	1585	900	340
Heat Joint	2832	2518	682
Tap-In Joint	1805	2676	497

The joints that use metallic inserts presented, on average, about 60% of the resistance of the threaded joints. In these cases, the variability of the obtained pullout force is essentially dependent on quality the inserting process. As mentioned before, the three insertion processes tested where: tap-in, glue and heated. During the tap-in process the alignment of the metallic insert with the hole is not easily achieved, which makes the process not very reliable. In the same way, the glue process also does not ensure a good repeatability, due to the difficulty in spreading the glue in a uniform way and control the drying process. These problems resulted in very low maximum average pullout force for the glued and tap-in M6 10mm sparse parts (see Table 3). More consistent results were achieved for the maximum average pullout force obtained on the M3 1mm sparse parts, while no valid tests were achieved for the glued and tap-in processes [see Table 4].

The heated process was found to be the most robust one, achieving the best average pullout force. Considering the overall average pullout force for the solid and 10mm sparse parts, it may be seen that the M6 part handled a 4 times bigger average pullout force than the M3 part. For the heated process on the 10 mm sparse part, the increase of the metallic insert for the M6 size resulted in an increasing to twice of the withstood force.

5 CONCLUSIONS

In this study a simple and expedite experimental methodology was used to compare pullout forces sustained by a threaded hole, with M3 and M6 diameters, made on an ABS-ESD7 part produced by using the FMD technique. Solid, 10mm sparse and 1mm sparse parts were compared. The results obtained exhibit a large dispersion indicating that they strongly depend on the way the thread was made and metallic insert was placed.

In general, the threaded joints with good quality presented higher strength to pullout forces than the joints with metallic inserts. Regarding the joints with metallic inserts, the heated process often achieved better results, sometimes very close to the threaded joints. On the other hand, the gluing process revealed itself to be the least robust. The tap-in process also showed a good robustness, obtaining, in general, 60% of the threaded joints resistance. Different pulling out force curves were obtained for the distinct cases studied. For threaded joints the pullout force rises rapidly until the maximum force is achieved, which corresponds to the material yield strength in the threaded zone. After the material starts to yield the force drops abruptly. For the inserted joints, a less steep increase of force was noted until the maximum force value was achieved, after which, the interface between the insert and the hole surface starts to yield and the force starts to slowly decrease ate the same rate as the contact area shrinks. For the 1 mm sparse parts, the material fails first than the threaded joints and insert joints, which leads therefore to similar curve profiles.

The 10mm sparse, either with M3 or M6 diameter, showed to be sufficient to guarantee a pullout force in the same order of magnitude as the solid parts. Although, only considering de 1mm sparse parts the pullout force dropped to, approximately 30% of the solid parts.

ACKNOWLEDGEMENTS

This work is supported by: *European Structural and Investment Funds* in the *FEDER* component, through the *Operational Competitiveness and Internationalization Programme* (COMPETE 2020) Project nº 002814; Funding Reference: POCI-01-0247-FEDER-002814” between Minho University and Bosch Braga, Portugal.

REFERENCES

ASTM International. (2012). *Standard Terminology for Additive Manufacturing Technologie. Pennsylvania*. EUA: West Conshohocken.

Bandypadhyay, A., & Bose, S. (2016). *Additive Manufacturing*. Florida, EUA: CRC Press, 6-10.

Bhosale, R. D., Nalawade, P. S., et al. (2017). *Study & Design of Jig and Fixture for Base frame of Canopy Fabrication of Generator*. International Research Journal of Engineering and Technology, 4 (5), 1592-12595.

Dieter, G. E., & Schmidt, L. C. (2000). *Engineering Design*. McGraw-Hill Education.

Eger, T., Eckert, C., & Clarkson, P. J. (2005). *The Role of Design Freeze in Product Development*. International Conference on Engineering Design.

Gebhardt, A. (2011). *Understanding Additive Manufacturing*. Munich, Germany: Hanser Publications.

Heilala, J., Voho, P., et al. (2001). *Assembly Process Level Tolerance Analysis for Electromechanical Products*. Proceedings of the 4th IEEE International Symposium on Assembly and Task Planning Soft Research Park, 405-406.

Inman, R. R., Huang, N., et al. (2010). *Designing production systems for quality: Research opportunities from an automotive industry perspective*. International Journal of Production Research, 41 (9), 1953-1971.

Kakish, J., Zhang, P., & Zeid, I. (2000). *Towards the design and development of a knowledge-based universal modular jigs and fixtures system*. Journal of Intelligent Manufacturing, 11, 381-401.

Kochan, D. (1993). *Solid Freeform Manufacturing: Advanced Rapid Prototyping*. B. V., Netherlands: Manufacturing Research Technology, Elsevier Publishers.

Levy, G., Schindel, R., et al. (2003). *Rapid Manufacturing and Rapid Tooling with Layer Manufacturing (LM) Technologies, State of the Art and Future Perspectives*. CIRP Annals—Manufacturing Technology, 52(2), 589-609.

Pham, D., & Gault, R. (1998). *A comparison of rapid prototyping technologies*. International Journal of Machine Tools and Manufacture, 38(10-11), 1257-1287.

Rahman, M. A., & Aziz, F. A. (2010). *Electrostatic discharge (ESD) improvement to reduce customer complaint*. Scientific Research and Essays, 5 (11), 3003-3008.

StrataSYS, D.M. (2016). *3D Printing JIGS & Fixtures for the Production Floor*. 9-11.

Wong, K. V., & Hernadez, A. (2012). *A Review of Additive Manufacturing*. ISRN Mechanical Engineering, 2012, 1-10.