Chapter

Analysis of the Performance of Drilling Operations for Improving Productivity

Majid Tolouei-Rad and Muhammad Aamir

Abstract

Drilling is a vital machining process for many industries. Automotive and aerospace industries are among those industries which produce millions of holes where productivity, quality, and precision of drilled holes plays a vital role in their success. Therefore, a proper selection of machine tools and equipment, cutting tools and parameters is detrimental in achieving the required dimensional accuracy and surface roughness. This subsequently helps industries achieving success and improving the service life of their products. This chapter provides an introduction to the drilling process in manufacturing industries which helps improve the quality and productivity of drilling operations on metallic materials. It explains the advantages of using multi-spindle heads to improve the productivity and quality of drilled holes. An analysis of the holes produced by a multi-spindle head on aluminum alloys Al2024, Al6061, and Al5083 is presented in comparison to traditional single shot drilling. Also the effects of using uncoated carbide and high speed steel tools for producing high-quality holes in the formation of built-up edges and burrs are investigated and discussed.

Keywords: drilling, cutting tools, hole quality, productivity, multi-spindle head

1. Introduction

Drilling is the most commonly performed machining operation in manufacturing industries. Therefore, the analysis and improvement of this process are of great importance in increasing productivity and competitiveness, where many existing studies reported on the optimization and improvement of this process [1, 2]. There are many machines that perform drilling operations including dedicated drilling machines, lathes, milling machines, machining centers and special purpose machines. The drilling process is extensively and heavily used in industries, accounting for a large portion of overall machining time and costs. Therefore, drilling has a significant economic role in industries, where it hugely contributes to the fabrication of various industrial parts [3].

Hole-making processes using drilling operations have been the focus of many research studies, where a lot of development and progress has been made. However, as technology has progressed and newer tools and equipment have been introduced, further research is required to improve the productivity and efficiency of this important operation, which forms the core of activities in many industries [4, 5].

For example, the heat exchangers of nuclear energy centrals require up to 16,000 holes in a single exchanger for assembly with refrigeration tubes [6]. Other examples include the automotive industry, where the drilling process forms up to 40% of total material removed [7], or the aerospace industry where millions of holes are required for joining various parts of aircraft fuselage [8]. It is estimated that 750,000 holes are required in a single wing of an Airbus A380, with 1.5–3 million holes as the requirements for producing a typical commercial aircraft [7]. Furthermore, over a million rivets are needed for large ships [9] where drilling is the primary process. Therefore, a proper selection of machine tools and equipment, cutting tools and parameters is essential in achieving required productivity, dimensional accuracy, and surface roughness. This subsequently helps industries achieve success and improve the service life of their products.

2. The drilling process

In the drilling process, holes are created when a cylindrical tool rotates against a workpiece, where a tool called a drill bit is used as shown in **Figure 1** [10, 11]. The drilling operation process involves three stages: the start and centering stage, the full drilling stage and the breakthrough stage [12]. In the first stage, the exact position of the hole is required, whereas the second stage leads to the full engagement of the drill bit, whilst the last stage includes passing the drill through the underside of the workpiece, where the operation stops [13].

A hole in the drilling process can be created in many forms, including blind and through holes, as shown in **Figure 2**. Blind holes are drilled to a certain depth whilst through-holes refer to the condition when the drill bit passes through the material and exits the workpiece on the other side [13].

Generally, a depth to diameter ratio of 5:1 or greater is commonly performed by twist drills, where this ratio may be doubled when using high-performance twist drills equipped with through-tool coolant systems. This ratio can be increased to roughly 20:1 when using special deep hole drilling tools equipped with through-tool coolant systems. Whilst this chapter focuses on the use of twist drills, it is worth-noting that a depth to diameter ratio of 100:1 or more is achievable in gun-drilling machines with through-tool coolant systems. Unlike conventional drilling operations, within gun-drilling machines both the cutting tool and workpiece rotate in opposite directions and at different rotational speeds, which significantly improves the straightness of the deep hole that is generated [14].

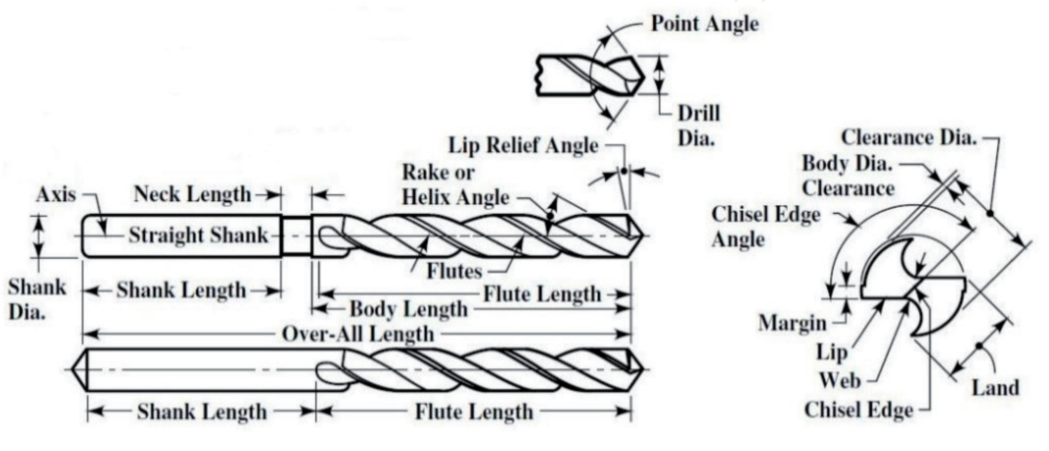

Figure 1.
Standard twist drill nomenclature [11].

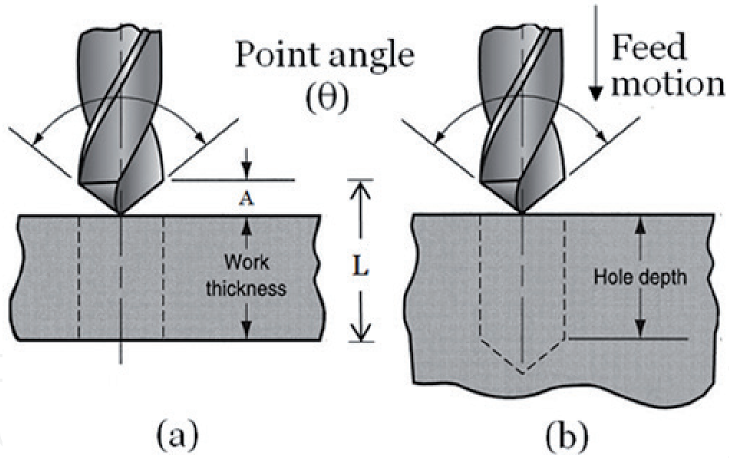

Figure 2.
Drilling process: (a) blind holes (b) through holes [10].

3. Cutting conditions in drilling process

To a large extent, cutting conditions determine the success of any drilling operation. Basic cutting conditions include cutting speed, feed rate, material removal rate, and machining time, as discussed in this section below.

3.1 Spindle speed and cutting speed

The spindle speed is the rotational speed measured in rev/min, calculated using a tachometer during the drilling process. The spindle speed is used to compute desired cutting speed, defined as the distance travelled by each cutting edge on the surface of the workpiece when cutting material. Therefore, cutting speed in a drilling operation is computed by.

$$v = \frac{\pi d n}{1000} \tag{1}$$

where v is the cutting speed in m/min, π = 3.14, d is the diameter of the cutting tool in mm, and n is the spindle speed in rev/min.

3.2 Feed and feed rate

In a drilling process feed is specified in mm/rev. The feed rate, which is the linear travel rate in mm/min, can be adjusted by a convenient system when the feed is multiplied by the spindle speed. Hence, feed rate can be found as.

$$f_r = fn \tag{2}$$

where f_r is the feed rate in mm/min, f is the feed in mm/rev, and n is the spindle speed in rev/min.

3.3 Material removal rate

The material removal rate can be considered as an index for the determination of the efficiency of a machining process. In a drilling process, material removal is obtained by [15].

$$M_{rr} = \left(\frac{\pi}{4}\right) d^2 f_r \tag{3}$$

where M_{rr} is the material removal rate in mm^3, d is the diameter of the drill in mm, and f_r is the feed rate in mm/min.

3.4 Drilling time

Drilling time is the time a tool is engaged from the beginning of chip production to the end for uninterrupted machining. Any pause during this process, either planned or unplanned, is not included in this time. The drilling time in minutes for through holes can be determined by [15].

$$T_m = \frac{L}{f_r} \tag{4}$$

where T_m is drilling time in minutes, L is the distance travelled by the cutting tool in mm, and f_r is the feed rate in mm/min.

It should be noted that the drill bit should travel the distance L (see **Figure 2**), which consists of the desired depth of the hole plus an allowance for the tool point angle, A, given by.

$$A = \frac{d}{2}\tan\left(90 - \frac{\theta}{2}\right) \tag{5}$$

where A is the allowance in mm, d is the diameter of the drill in mm, and θ is the tool point angle in degrees.

4. Aluminium alloys

Aluminium and its alloys are very attractive to many manufacturing industries due to its unique combinations of properties with outstanding engineering applications across various industries [16, 17]. Aluminium has low density, reasonably high strength, high ductility, high thermal and electrical conductivities, good oxidation and corrosion resistance, easy to manufacture and has a relatively low cost [18].

The high strength-to-weight ratio of aluminium alloys makes them suitable for wide use in marine, automotive and aerospace industries [19]. The various grades of aluminium alloys used in the aviation industry can be found in reference [5]. Aluminium and its alloys are also used in home appliances, construction industries, electrical, electronic, packaging industries, etc. [16, 19].

Aluminium alloys are divided into workable alloys and cast alloys. Alloys of aluminium that undergo hot or cold mechanical working processes are termed as workable alloys, while those whose shape is obtained by the casting process are known as cast alloys [19].

Aluminium alloys are generally considered more machinable than ferrous alloys; however, their ductile nature results in high machining forces, poor surface roughness and difficult control of chips, whereas those with hard particles can cause high tool wear [19].

5. Multi-spindle drilling for productivity improvement

Multi-spindle drilling is used in manufacturing industries to improve productivity as they can drill many holes simultaneously, which reduces machining time significantly. The multi-spindle or poly-drill head gives high center-to-center accuracy and in many instances eliminates the need for the use of drilling jigs, and this further decreases drilling time and cost. Therefore, in today's competitive market, it is essential to produce a large number of products at the right time with high quality and at minimum cost, where the use of a multi-spindle drill head is one way to fulfil this goal. A multi-spindle drill head can simultaneously drill from two to ten or more holes on the same plane [20]. The multi-spindle drill head produces a number of holes of similar quality in the most economical way, providing a high level of automation with a small investment [21].

Multi-spindle drilling technology is used to increase productivity whilst reducing machining time in working conditions where a large number of closely-spaced holes need to be drilled. A good example of this is the manufacturing of aircraft fuselage and construction of metal bridges, where a large number of riveting holes are required. **Figure 3** shows a section of the Golden Gate Bridge which has been constructed using a large number of rivets. It is estimated that approximately 600,000 rivets are used in this structure [22].

Multi-spindle or poly-drill heads are mounted on a machine tool to perform many operations simultaneously [23]. Multi-spindle drill heads are either fixed or flexible. The tool positions in fixed multi-spindle drill heads cannot change. Whereas in the flexible type the positions of tools can be adjusted as needed within a particular range [24]. **Figure 4** shows an adjustable 3-spindle drill head [25]. The importance of using this poly drill head instead of using a single drill bit is the possibility of producing high quality drilled holes, the elimination of a drilling jig for maintaining a high center-to-center tolerance, fewer rejections, reducing

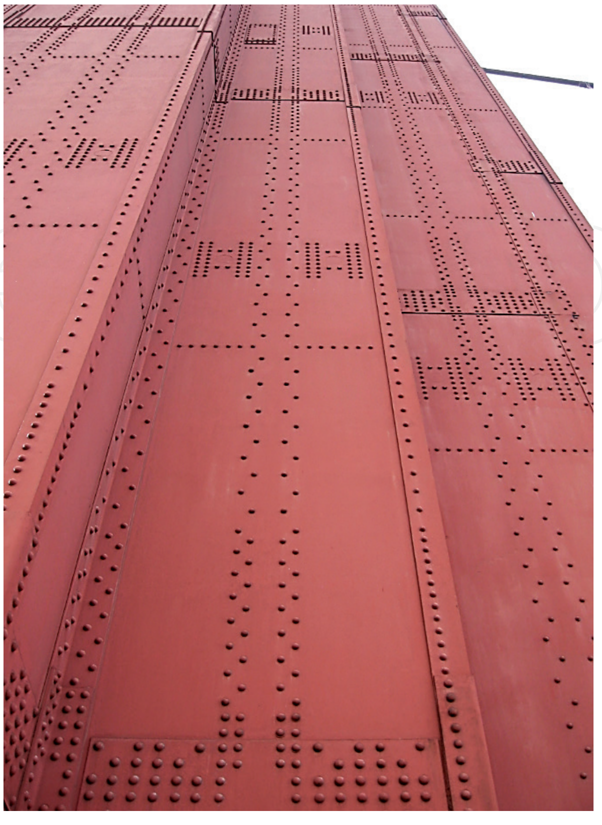

Figure 3.
Thousands of rivets are used in the structure of the Golden Gate Bridge, San Francisco, United States.

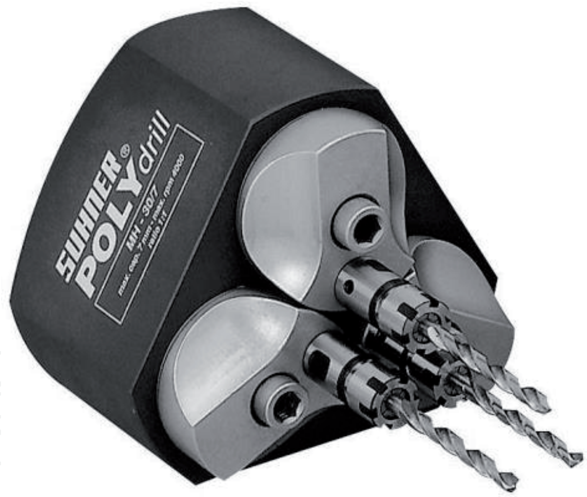

Figure 4.
An adjustable 3-spindle drill head [25].

machining time, increasing profit rate and less operator fatigue [26]. Therefore, it is worth noting that the use of multi-spindle drilling is an excellent choice to improve productivity and reduce machining time for manufacturing industries requiring the production of a large number of holes with stringent tolerances. Therefore, the advantages of using the multi-spindle head are listed below [23]:

- The increase in productivity at a higher rate
- The performance of multiple operations in one cycle
- The time for one hole is the time for multiple numbers of holes
- The multi-spindle drilling ensures positional accuracy
- Elimination or reduction of the need for drilling jigs
- Less quality control rejections
- Easy to install and use anywhere
- Easy to operate and low maintenance
- Simple in construction and robust in design

5.1 Cutting mechanisms in the drilling of aluminium

In the machining process, when a tool penetrates inside a metal workpiece, it produces an internal shearing action in the metal where the metal becomes severely stressed. This causes the metal to be plastically deformed and flow in the form of chips when the ultimate shear strength of the metal is exceeded [27]. In the drilling process, the thrust force is the perpendicular force to the workpiece during its translational motion while the torque comes from the machine spindle to rotate the tool during drilling operation. Other forces in drilling are not important as they are small compared to the thrust force [28]. It should be noted that high cutting forces affect hole quality and tool life [29]. Forces generated in the drilling of metals are uniform where uncut chip thickness is constant [30].

Experimental studies have shown that thrust force generated in multi-spindle drilling is higher than that obtained in one-shot single drilling processes of aluminum alloy Al5083 [31]. The higher thrust force occurs due to the combination of more than one tool operating simultaneously in one go. However, the results of experiments have concluded that the average of all the tools' thrust force per tool in multi-spindle drilling was slightly lower than the thrust force resulting from single drilling [31]. In addition to thrust force, another important parameter in a drilling process is the increase in cutting temperature [32]. A higher cutting temperature increases the ductility of the material which results in the formation of long chips, which negatively affects the hole quality [33]. A high temperature may also increase the chemical interaction between aluminium and the tool coating that is responsible for inter-atomic diffusion [34]. The cutting temperature increases due to heat generation which is the result of an increase in cutting speed [35].

Further, in machining ductile materials like aluminium, there is a chance of producing continuous chips due to the plastic deformation of its ductile nature. Other factors that contribute to the formation of continuous chips are high cutting speed, sharp cutting edge, etc. Continuous chips are not easy to handle and dispose of, where they can get tangled around the tool and pose safety issues to the operator. Additionally, when a tool face is in contact for a long time, it results in more frictional heat and affects machining. Therefore, discontinuous and segmented chips produce less friction between the tool and chip; hence, resulting in a better surface finish and providing higher operator safety [27].

5.2 Cutting tool and spindle adjustment in multi-spindle drilling of aluminium alloys

As mentioned earlier, the best performance in a drilling process is obtained when using appropriate cutting tools, where the correct process conditions are used to reduce the level of damage as much as possible [27]. The most commonly used drill bit is the twist drill, as shown in **Figure 1**, which represents the industrial standard [36]. The important features of the twist drill include the point angle, clearance angle, chisel edge angle, drill diameter, web thickness, the rake angle, etc. The rake angle in drills is specified as the helix angle [13]. The high point angle and large helix angle are recommended for better hole quality and less tool wear [37]. The large point angle also contributes to producing thinner chips during the machining of aluminium alloys [38]. However, the point angle should be selected based on silicon contents in aluminium alloys [39].

Experimental studies performed in references [31, 40] have shown that tools used for multi-spindle drilling give less formation of built-up edges as compared to the single drilling process of aluminum alloy Al5083 due to differences in chip size when uncoated High-Speed Steel (HSS) drills with a point angle of 118° and size of 6 mm were used. The experiments were conducted using a conventional milling machine for both single drilling and multi-spindle drilling processes, and the same drilling parameters and conditions were applied. For the multi-spindle drilling process, a SUNHER poly-drill head, as shown in **Figure 5**, was used.

Multi-spindle drilling experiments were further extended and uncoated HSS drills were tested on aluminium alloy Al2024 and compared with uncoated carbide drills with a point angle of 140° and a diameter of 6 mm. Apart from aluminum alloy Al2024, the 6 mm uncoated carbide drills were also used for multi-spindle drilling of aluminium alloys Al5083 and Al6061. In addition, 6 mm uncoated carbide drills were used to compare different center-to-center tool distances of the spindle in the multi-spindle drilling process. Further, a comparison of 6 mm and 10 mm uncoated carbide drills with the same point angle of 140° were also made [41, 42].

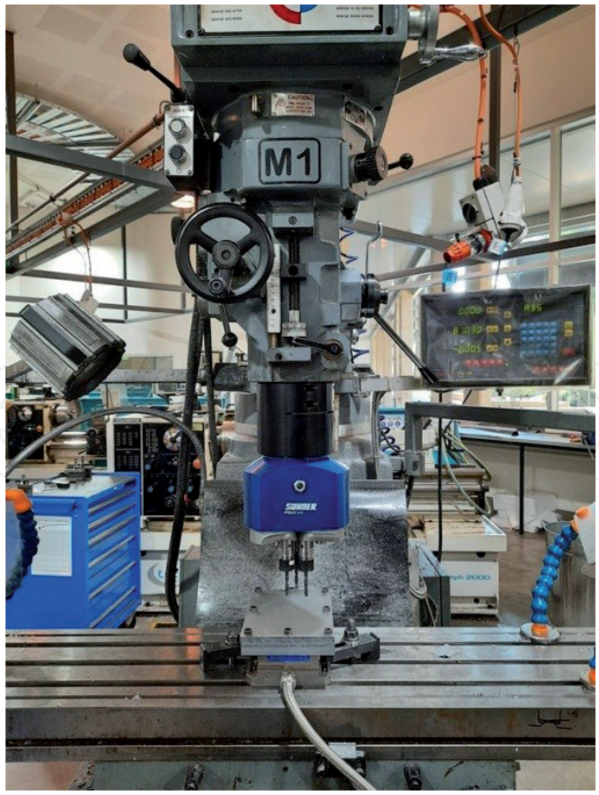

Figure 5.
The 3-spindle Suhner multi-spindle drill head mounted on conventional milling machine (Courtesy: Edith Cowan University, Australia).

In general, the uncoated carbide drill has been recommended in multi-spindle drilling of aluminium as compared to the uncoated HSS drills due to the high built-up edge formation because of its moderate strength, as shown in **Figure 6**. The drill diameter did not show any significant changes in affecting the hole quality; however, the larger drill size covered a larger cross-sectional area that resulted in a higher thrust force and producing larger chips. Therefore, for the smaller drill size, an easier chip breaking and evacuation was resulted. Furthermore, the larger point angle of 140° - compared to 118° - provided a better hole quality but did not contribute to changing the size or shape of the chips.

The tool conditions from **Figure 6** also shows that when drilling aluminium alloy Al5083, a large built-up edge was formed, which was expected due to low silicon contents, where this is in agreement with research conducted by Akyüz [43] in which alloys with low silicon contents produce a high built-up edge. Additionally, the low hardness value of the material used in this operation might be another cause of high formation of the built-up edge because alloys with low hardness values have a high tendency towards the formation of built-up edges [44].

Multi-spindle drilling is useful in its easy adjustment of tools. Depending on the type and use, the tools of a multi-spindle head can be adjusted to any position without affecting the results, which not only increases productivity at a high rate but also produces high-quality holes. This is performed at the same time, whereas only a single hole is produced in one-shot single drilling process without a compromise on the hole quality.

5.3 Quality assessment of drilled holes in multi-spindle drilling of aluminium

In any drilling process, it is important to ensure that damage-free and precise holes are produced to avoid rejection of parts [45]. For example, poor hole quality has been observed in 60% of aircraft components [5], which is of course a

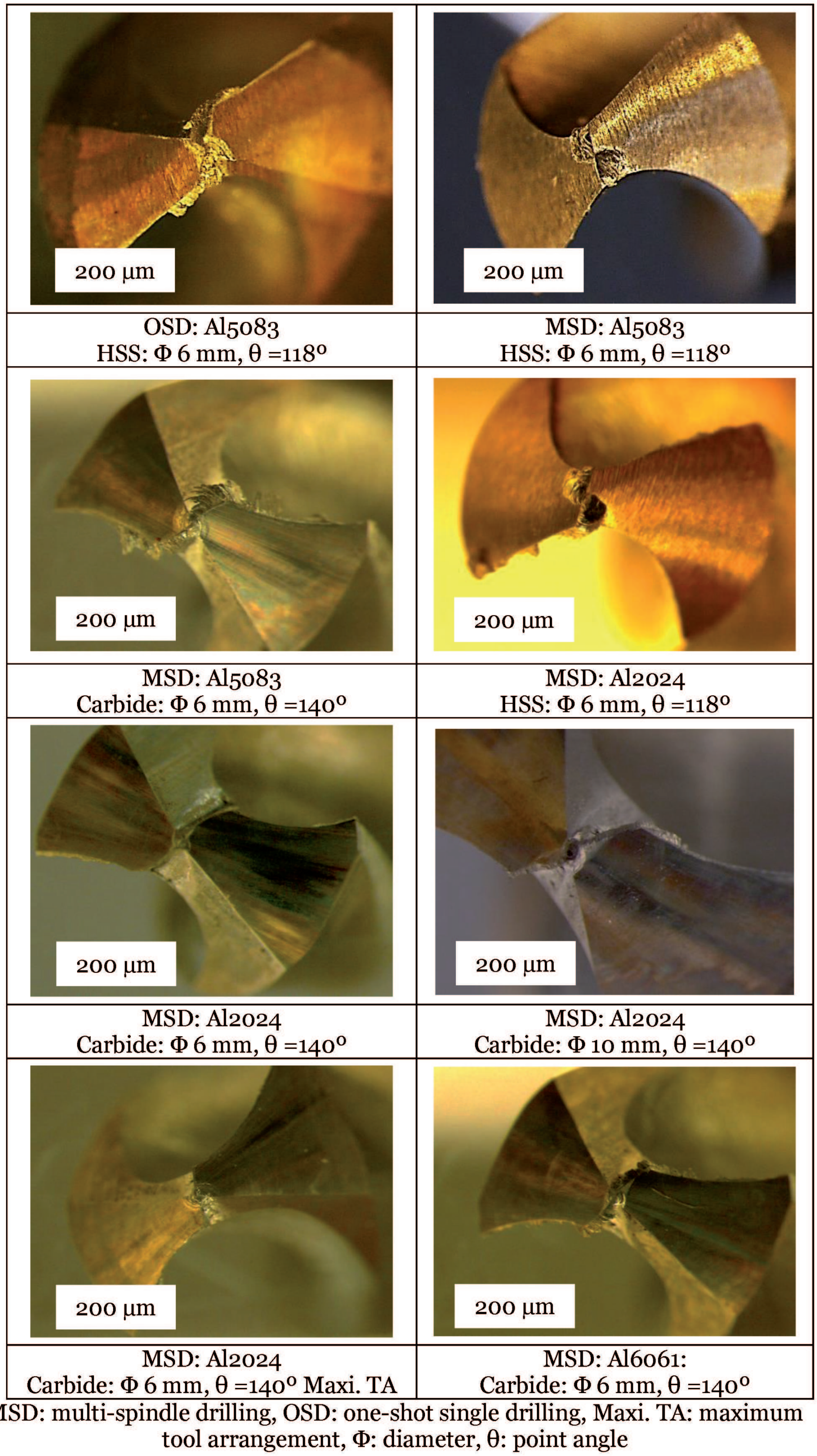

Figure 6.
Tool conditions after performing the drilling operation on different types of aluminium alloys using the multi-spindle drill head.

challenging problem. Hence, there is a need to control the number of rejected parts by overcoming problems related to the drilling process, especially the quality of drilled-holes [45]. A poor quality hole can create regions of concentrated stress that increase the chances of formation of fatigue cracks, which reduces the reliability of products [46]. Desirable hole quality in drilling operations can be achieved by proper selection of drilling process parameters, appropriate cutting tools, and machine setup [47].

In the experimental study by Aamir et al. [31], a single drilling process was compared with multi-spindle simultaneous drilling of aluminium alloy Al5083 using uncoated HSS tools. The drill diameter was 6 mm and the point angle was 118°. All drilling experiments were conducted using the same cutting parameters and in a dry environment. The hole quality produced by multi-spindle drilling was better than those obtained in a single-spindle drilling process. The holes drilled by the multi-spindle head had a lower surface roughness and fewer burrs around the holes. This was expected due to differences in chip formation.

Hole quality in a drilling process is also affected by the chemical composition and mechanical properties of aluminium alloys. An experimental study in multi-spindle drilling of aluminium alloys Al5083, Al6061, and Al2024 by Aamir et al. [42] concluded that regardless of drilling parameters, low surface roughness was obtained in aluminium alloy Al6061 due to its high silicon content. Literature has shown that alloys with high silicon content result in low surface roughness irrespective of drilling parameters [43, 48]. Furthermore, the reason for high surface roughness of aluminium alloy Al5083 might be due to the poor machinability and low hardness [44].

Aamir et al. [42] observed that less burrs formed around the hole edges of aluminium alloy Al2024 due to its good machinability compared with the aluminium alloys Al6061 and Al5083. Further, the less ductile nature of aluminium alloy Al6061 - in comparison with aluminium alloy Al5083 - resulted in the low formation of burrs. Hence, high ductility and poor machinability properties led to the formation of more burrs in aluminium alloy Al5083 [49]. Additionally, uncoated HSS drills produced low-quality holes by giving high surface roughness and more formation of burrs around the edges of holes due to the high built-up edges because of its moderate strength. Moreover, a larger point angle of 140° - compared to 118°- and a smaller diameter of 6 mm - in comparison to a drill size of 10 mm – have been recommended for multi-hole simultaneous drilling of aluminium alloys. However, the drill diameter did not show any significant effect on hole quality including the surface roughness and burrs [41]. **Figure 7** shows the quality of holes in terms of burr formation in multi-spindle drilling of aluminium alloys.

Regardless of drilling parameters, the workpiece materials and different tools, the surface roughness increases with increasing the cutting speed and feed rate. The likely reasons for high surface roughness at high cutting speeds might include the increase in workpiece deformation due to rise in temperature and the chances of high vibrations exerted by the tools [7, 47]. The high cutting speed and feed rate are responsible for the formation of burrs that reduces the hole quality. However, the high impact is due to the feed rate because stable, jerk-free and slow insertions of drills are possible with low feed rates which form thin chips; hence, the hole quality is less affected [50]. Further, according to Costa et al. [51], any factor that causes the generation of high thrust force results in more formation of burrs, and the high feed rate increases thrust force. Additionally, due to less formation of burrs, the tool entry side of the holes was found to be better than those on the tool exit side. This is likely due to the different mechanism of burr formation at the entry and exit sides of the holes. According to Zhu et al. [52], the tearing occurs as a bending action followed by clean shearing or lateral extrusion causing entrance burrs while exit

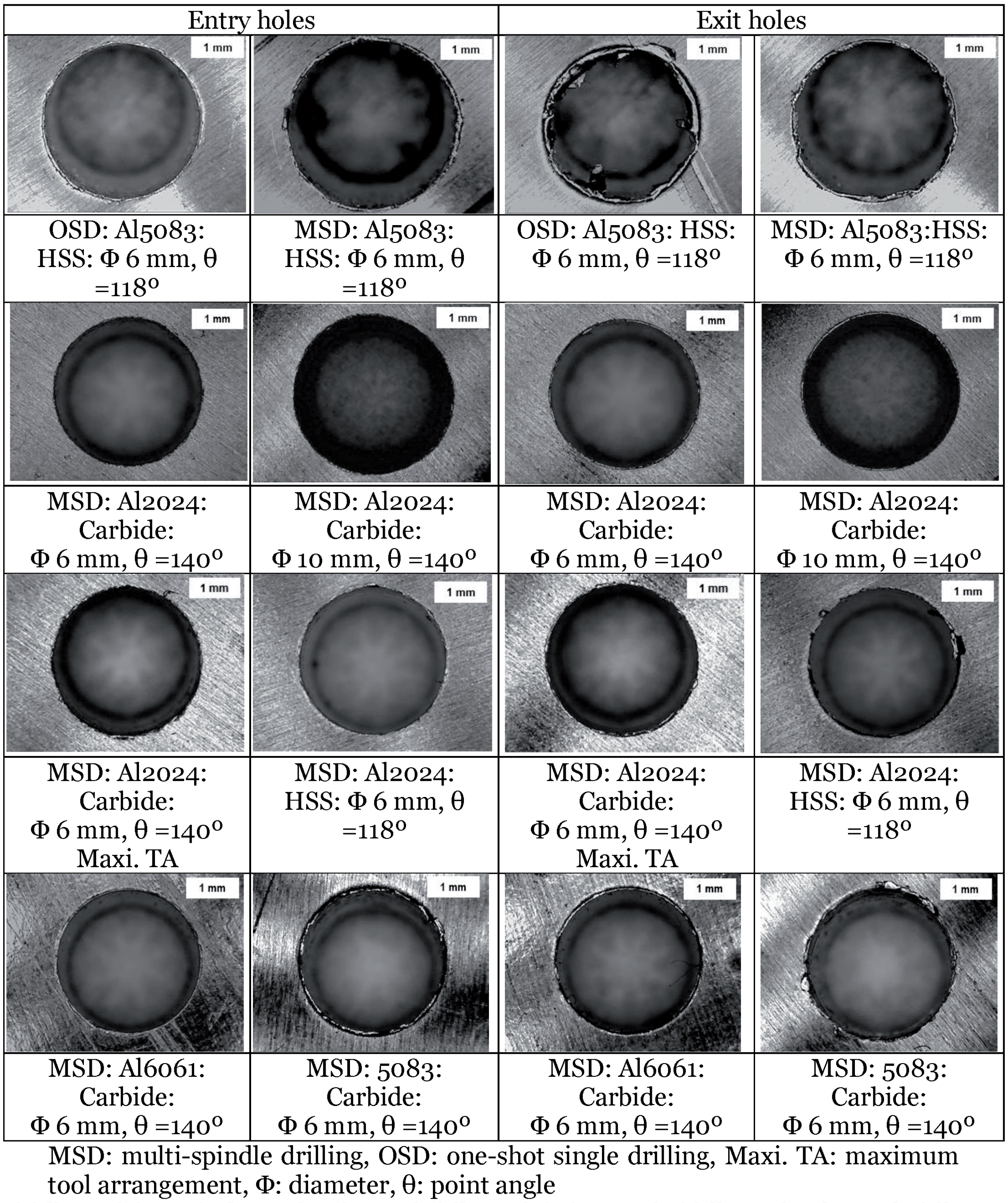

Figure 7.
Hole quality in terms of burr formation in multi-spindle drilling of aluminium alloys using the multi-spindle head.

burrs formed as a result of plastic deformation of the materials. Besides this, low temperature and thrust force are the reasons for small burrs on the entry side of the hole which can be removed by chamfering [53].

6. Conclusions

Many industries, such as automotive and aerospace, produce millions of holes per day where productivity, quality, and precision of drilled holes plays a vital role in their success. Multi-spindle drilling is capable of producing more drilled-holes with higher rates, which makes it advantageous in high-volume production with uniform qualities, simultaneous machining, and most importantly reducing the drilling time which is one of the important factors in achieving greater productivity.

Therefore, the production of a large number of closely-spaced holes simultaneously by using a poly-drill or multi-spindle drill head results in achieving higher productivity and quality. This approach not only enhances the competitiveness of the process but also results in cost reduction and uniformity of generated holes.

Further, it can be concluded that hole quality is affected by drilling parameters and properties of the workpiece. Alloys of aluminium with high silicon contents show lower values of surface roughness while those with low hardness and poor machinability provide poor hole quality. The experiments also show that uncoated carbide tools are more suitable compared to uncoated HSS for producing high-quality holes, resulting in the formation of less built-up edges when drilling aluminium alloys. Moreover, the aluminium alloy Al2024 produced better results in terms of hole quality due to its good machinability compared with aluminum alloys Al6061 and Al5083.

Acknowledgements

The authors would like to thank Edith Cowan University, Australia for the awarded (ECU-HDR) higher degree research scholarship and for providing support on this research.

Conflict of interest

The authors declare no conflict of interest.

Author details

Majid Tolouei-Rad* and Muhammad Aamir
School of Engineering, Edith Cowan University, Joondalup, WA, Australia

*Address all correspondence to: m.rad@ecu.edu.au

References

[1] Vafadar A, Hayward K, Tolouei-Rad M. Drilling reconfigurable machine tool selection and process parameters optimization as a function of product demand. Journal of Manufacturing Systems. 2017;45:58-69.

[2] Tolouei-Rad M, Shah A. Development of a methodology for processing of drilling operations. International Journal of Industrial and Manufacturing Engineering. 2012;6(12):2660-2664.

[3] Kilickap E. Modeling and optimization of burr height in drilling of Al-7075 using Taguchi method and response surface methodology. The International Journal of Advanced Manufacturing Technology. 2010;49(9-12):911-923.

[4] Aamir M, Tolouei-Rad M, Giasin K, Nosrati A. Recent advances in drilling of carbon fiber–reinforced polymers for aerospace applications: a review. The International Journal of Advanced Manufacturing Technology. 2019;105(5-6):2289-2308.

[5] Aamir M, Giasin K, Tolouei-Rad M, Vafadar A. A review: drilling performance and hole quality of aluminium alloys for aerospace applications. Journal of Materials Research and Technology. 2020;9(6):12484-12500.

[6] De Lacalle LL, Fernández A, Olvera D, Lamikiz A, Rodríguez C, Elias A. Monitoring deep twist drilling for a rapid manufacturing of light high-strength parts. Mechanical systems and signal processing. 2011;25(7):2745-2752.

[7] Giasin K, Hodzic A, Phadnis V, Ayvar-Soberanis S. Assessment of cutting forces and hole quality in drilling Al2024 aluminium alloy: experimental and finite element study. The International Journal of Advanced Manufacturing Technology. 2016;87(5-8):2041-2061.

[8] Rivero A, Aramendi G, Herranz S, de Lacalle LL. An experimental investigation of the effect of coatings and cutting parameters on the dry drilling performance of aluminium alloys. The International Journal of Advanced Manufacturing Technology. 2006;28(1-2):1-11.

[9] Felkins K, Leigh H, Jankovic A. The royal mail ship Titanic: Did a metallurgical failure cause a night to remember? JOM Journal of the Minerals, Metals and Materials Society. 1998;50(1):12-18.

[10] Groover M. Fundamental of modern manufacturing: Materials,Processes, andSystems. USA: John Wiley & Sons, Inc; 2004.

[11] Oberg E. Machinery's Handbook 29th Edition-Full Book: Industrial Press; 2012.

[12] Tönshoff H, Spintig W, König W, Neises A. Machining of holes developments in drilling technology. CIRP annals. 1994;43(2):551-561.

[13] Sharif S, Rahim EA, Sasahara H. Machinability of titanium alloys in drilling. Titanium Alloys-Towards Achieving Enhanced Properties for Diversified Applications. 32012. p. 117-137.

[14] Systems UDHD. What is Gun Drilling? 2020. Available from: https://unisig.com/information-and-resources/what-is-deep-hole-drilling/what-is-gun-drilling/.

[15] Girsang IP, Dhupia JS. Machine Tools for Machining. In: Nee AYC, editor. Handbook of Manufacturing Engineering and Technology. London: Springer London; 2015. p. 811-865.

[16] David J. Aluminum and Aluminum alloys. Alloying: Understanding the

basics. ASM International, Ohio; 2001. p. 351-416.

[17] Aamir M, Tolouei-Rad M, Vafadar A, Raja MNA, Giasin K. Performance Analysis of Multi-Spindle Drilling of Al2024 with TiN and TiCN Coated Drills Using Experimental and Artificial Neural Networks Technique. Applied Sciences. 2020;10(23):8633.

[18] Campbell FC. Aluminum. Elements of Metallurgy and Engineering Alloys: ASM International; 2008. p. 487-508.

[19] Santos MC, Machado AR, Sales WF, Barrozo MA, Ezugwu EO. Machining of aluminum alloys: a review. The International Journal of Advanced Manufacturing Technology. 2016;86(9-12):3067-3080.

[20] Tolouei-Rad M. An intelligent approach to high quantity automated machining. Journal of Achievements in Materials and Manufacturing Engineering. 2011;47(2):195-204.

[21] Tolouei-Rad M. Intelligent analysis of utilization of special purpose machines for drilling operations. Intelligent Systems, Prof Vladimir M Koleshko (Ed), ISBN: 978-953-51-0054-6, InTech, Available from: http://wwwintechopencom/books/intelligent-systems/intelligent-analysis-of-utilization-of-special-purposemachines-for-drilling-operations. Croatia2012. p. 297-320.

[22] Golden Gate Bridge HaTD. Frequently Asked Questions about the Golden Gate Bridge: How many rivets are in each tower of the Golden Gate Bridge 2020. Available from: https://www.goldengate.org/bridge/history-research/statistics-data/faqs/.

[23] Tam BN, Van Dich T. Research, Design and Develop a prototype of Multi-Spindle Drilling Head. Journal of Science & Technology. 2018;127:029-034.

[24] Tolouei-Rad M. An efficient algorithm for automatic machining sequence planning in milling operations. International Journal of Production Research. 2003;41(17):4115-4131.

[25] Tolouei-Rad M, Zolfaghari S. Productivity improvement using Special-Purpose Modular machine tools. International Journal of Manufacturing Research. 2009;4(2):219-235.

[26] Vafadar A, Tolouei-Rad M, Hayward K, Abhary K. Technical feasibility analysis of utilizing special purpose machine tools. Journal of Manufacturing Systems. 2016;39:53-62.

[27] Sobri SA, Heinemann R, Whitehead D. Carbon Fibre Reinforced Polymer (CFRP) Composites: Machining Aspects and Opportunities for Manufacturing Industries. Composite Materials: Applications in Engineering, Biomedicine and Food Science. Cham: Springer International Publishing; 2020. p. 35-65.

[28] Tyagi R. Processing Techniques and Tribological Behavior of Composite Materials: IGI Global; 2015.

[29] Xu J, Mkaddem A, El Mansori M. Recent advances in drilling hybrid FRP/Ti composite: a state-of-the-art review. Composite Structures. 2016;135:316-338.

[30] Sheikh-Ahmad JY. Machining of polymer composites: Springer; 2009.

[31] Aamir M, Tu S, Giasin K, Tolouei-Rad M. Multi-hole simultaneous drilling of aluminium alloy: A preliminary study and evaluation against one-shot drilling process. Journal of Materials Research and Technology. 2020;9(3):3994-4006.

[32] Kelly J, Cotterell M. Minimal lubrication machining of aluminium alloys. Journal of Materials Processing Technology. 2002;120(1-3):327-334.

[33] Ozcatalbas Y. Chip and built-up edge formation in the machining of in situ Al4C3–Al composite. Materials & design. 2003;24(3):215-221.

[34] Roy P, Sarangi S, Ghosh A, Chattopadhyay A. Machinability study of pure aluminium and Al–12% Si alloys against uncoated and coated carbide inserts. International Journal of Refractory Metals and Hard Materials. 2009;27(3):535-544.

[35] Yousefi R, Ichida Y. A study on ultra–high-speed cutting of aluminium alloy:: Formation of welded metal on the secondary cutting edge of the tool and its effects on the quality of finished surface. Precision engineering. 2000;24(4):371-376.

[36] Panchagnula KK, Palaniyandi K. Drilling on fiber reinforced polymer/nanopolymer composite laminates: a review. Journal of materials research and technology. 2018;7(2):180-189.

[37] Nouari M, List G, Girot F, Coupard D. Experimental analysis and optimisation of tool wear in dry machining of aluminium alloys. Wear. 2003;255(7-12):1359-1368.

[38] Stephenson DA, Agapiou JS. Metal cutting theory and practice: CRC press; 2005.

[39] Davim JP. Modern machining technology: A practical guide. UK: Elsevier; 2011. 412 p.

[40] Aamir M, Tu S, Tolouei-Rad M, Giasin K, Vafadar A. Optimization and modeling of process parameters in multi-hole simultaneous drilling using taguchi method and fuzzy logic approach. Materials. 2020;13(3):680.

[41] Aamir M, Tolouei-Rad M, Giasin K, Vafadar A. Feasibility of tool configuration and the effect of tool material, and tool geometry in multi-hole simultaneous drilling of Al2024. The International Journal of Advanced Manufacturing Technology. 2020;111(3):861-879.

[42] Aamir M, Tolouei-Rad M, Giasin K, Vafadar A. Machinability of Al2024, Al6061, and Al5083 alloys using multi-hole simultaneous drilling approach. Journal of Materials Research and Technology. 2020;9(5):10991-11002.

[43] Akyüz B. Effect of silicon content on machinability of AL-SI alloys. Advances in Science and Technology Research Journal. 2016;10(31):51--57.

[44] Ratnam M. Factors affecting surface roughness in finish turning. In: Comprehensive materials finishing. Elsevier. 2017;1(1):1-25.

[45] Arul S, Vijayaraghavan L, Malhotra S, Krishnamurthy R. The effect of vibratory drilling on hole quality in polymeric composites. International Journal of Machine Tools and Manufacture. 2006;46(3-4):252-259.

[46] Liu J, Xu H, Zhai H, Yue Z. Effect of detail design on fatigue performance of fastener hole. Materials & Design. 2010;31(2):976-980.

[47] Kurt M, Kaynak Y, Bagci E. Evaluation of drilled hole quality in Al 2024 alloy. The International Journal of Advanced Manufacturing Technology. 2008;37(11-12):1051-1060.

[48] Kamiya M, Yakou T, Sasaki T, Nagatsuma YJMt. Effect of Si content on turning machinability of Al-Si binary alloy castings. 2008:0801280304-.

[49] Committee AH. Metals Handbook: Vol. 2, Properties and selection–nonferrous alloys and pure metals. American Society for Metals, Metals Park, OH. 1978.

[50] Uddin M, Basak A, Pramanik A, Singh S, Krolczyk GM, Prakash C. Evaluating hole quality in drilling of Al 6061 alloys. Materials. 2018;11(12):2443.

[51] Costa ES, Silva MBd, Machado AR. Burr produced on the drilling process as a function of tool wear and lubricant-coolant conditions. Journal of the Brazilian Society of Mechanical Sciences and Engineering. 2009;31(1):57-63.

[52] Zhu Z, Guo K, Sun J, Li J, Liu Y, Zheng Y, et al. Evaluation of novel tool geometries in dry drilling aluminium 2024-T351/titanium Ti6Al4V stack. Journal of Materials Processing Technology. 2018;259:270-281.

[53] Shanmughasundaram P, Subramanian R. Study of parametric optimization of burr formation in step drilling of eutectic Al–Si alloy–Gr composites. Journal of Materials Research and Technology. 2014;3(2):150-157.