A Mini Review on Machining of Aluminum

RM Magabe
Department of Mechanical and Industrial Engineering Technology
University of Johannesburg, Johannesburg,
Johannesburg, Republic of South Africa
200670741@student.uj.ac.za

Sujeet Kumar Chaubey
Department of Mechanical and Industrial Engineering Technology
University of Johannesburg, Johannesburg,
Johannesburg, Republic of South Africa
schaubey@uj.ac.za

Kapil Gupta
Department of Mechanical and Industrial Engineering Technology
University of Johannesburg, Johannesburg,
Johannesburg, Republic of South Africa
kgupta@uj.ac.za

Abstract

In this article, a review of the available literature on the machining (specifically turning) of aluminum is systemically presented. Through this work, a fundamental understanding of the machining of aluminum was developed together with the understanding of the effects of process parameters on machinability indicators. Selected articles from the past two decades have been considered. Turning of aluminum using different cutting tool inserts under different machining environments is presented. Out of the literature discussed, some are based on the modelling and optimization of turning parameters to facilitate the machining of aluminum. Overall, it can be concluded that since aluminum is a soft material and therefore difficult-to-machine, that necessitates various interventions like sustainable cooling and lubrication, tool treatment and texturing, and process optimization, to obtain the desired machinability.

Keywords
Aluminum, Machinability, Material removal rate, Surface roughness, Tool wear

1. Introduction
Due to some superior mechanical properties, aluminum has succeeded in replacing steel and cast iron in the fabrication of parts for the aerospace and automobile industries (Stanojkovic and Radovanovic 2022, Qazi et al. 2021). Since the 1930s, aluminum alloys have been used in the construction of aircraft components and have since been the go-to material for industries where a high strength-to-weight ratio is vital in part production (Totten and MacKenzie 2003). In other words, the demand by the automobile and aerospace industries for lighter, durable, and environmentally friendly materials for manufacture makes aluminum and its alloys a suitable material which is of major research focus these days. Its availability and the vast area of the application make aluminum the ideal material for such research. Aluminum alloys are classified by four major factors, namely cast, wrought, strain hardenable, and heat treatability (Mário et al. 2016). These factors also impact the machinability of the materials and thus machinability groupings are also used in the classification. The principal alloying elements are detrimental to the tool selection and machining parameters in order to ensure an economic process. In the case of cast alloys, machinability challenges are imposed by those that contain copper, magnesium, or zinc as the principal alloying element, such that the tool rake angle has to be considered. A small rake angle is normally preferred on the tool since it produces little danger of burring the part (Mário et al. 2016, Okokpujie and Tartibu 2022). The aluminum alloy 7075 is one of the strongest aluminum alloys that can effectively replace steel in strength and keep most of the desirable properties of aluminum (Soren et al. 2019).

Its strength is comparable to most steels. It has good fatigue strength and average machinability. This alloy has less resistance to corrosion owing to zinc being the primary alloying element. It finds applications in highly stressed structural parts which include, aircraft fittings, fuse parts, regulating valves, and various other commercial aircraft and defense equipment.

Difficult to machine materials (DTM) are materials that present a multitude of problems during machining operations. These materials range from very hard materials (titanium alloys) to very light materials (aluminum alloys) and they vary in the challenges they present. In the turning operation, a variety of challenges constitute the difficulty in the machining of these materials (Pandi and Muthusamy 2012).

The machining of aluminum requires an understanding of the properties of the material and its application. The "soft" nature of aluminum and its alloys has both positive and negative effects during the machining processes. They can be machined more rapidly and economically when compared to other materials (Yeganefar et al. 2019). Studies show that the power required to machine an aluminum alloy is considerably less when compared to that needed to turn a low-carbon steel of approximately the same hardness and tensile properties due to the reduced cutting force required during machining.

The high ductility and low modulus of elasticity increase the tendency for aluminum alloys to stick to machining tools during machining. These properties impart these alloys the attribute of softness when compared to ferrous alloys which is responsible for the machining challenges while a high silicon content in aluminum-silicon alloys contributes to a high cutting tool wear rate. It is for these reasons that machining an aluminum alloy requires a fine cutting edge and a high clearance angle on the cutting tool together with a positive rake angle which is high on both back and side (Yeganefar et al. 2019). This is to prevent or reduce a built-up edge on the cutting tool.

2. Literature Review

Upon conducting experiments to identify optimal process parameter combination to minimize SR, roundness, and maximize MRR, Jayaraman and Kumar (2014) found that the FR and DOC were the prominent factors in the turning of AA 6063 T6 using an uncoated carbide insert under dry cutting conditions. They found that FR affects machining at 57.365%, DOC at 25.11% and CS at 17.35%. These experimental results yielded a Grey Relational Grade (GRG) of 0.7717 with the best values of the considered machinability indicators surface roughness, roundness, and MRR, obtained at a CS of 119.22 m/min, FR of 0.05 mm/rev and DOC of 0.15mm. Rotella et al. (2019) conducted research on the analysis and optimization of surface quality using Al7075 following the grey relational analysis. They found that increasing CS, FR and DOC increases the MRR. Their investigation yielded optimum results of 0.64µm for SR and a MRR of 28.63 mm3/min at 283 m/min CS, 0.17mm/rev FR and 0.68 mm DOC using a nose radius of 1.2mm. Upon analysis of results, they found that FR has the highest % contribution when it comes to circularity error, followed by DOC and nose radius. Rao et al. (2017) investigated micro hardness and residual stress induced during turning of Al7075. They found that CS and DOC have detrimental effect on the surface residual stresses with the micro hardness decreasing with the increase in the DOC. The cutting force increases with the increase in DOC and is not affected by CS at a given DOC. The surface roughness 0.72 µm was obtained at a CS of 200 m/min. In an important study, Eapen et al. (2017) conducted machining of AA6063 in a cryogenic precooled and dry environment and found that the ductility of AA6063 prevents effective chip formation. They also found pre cooled conditions favour better SR and yield a better reduction coefficient at low and medium speeds. Ahmed et al. (2017) used carbide inserts on Al6351 T6 following Taguchi design of experiment to determine the SR and MRR achievable for a turning operation. They found the order of effectiveness on SR to be- nose radius, DOC, FR and CS whereas the order for MRR is DOC, FR, CS and nose radius. The best SR result parameters were found to be: CS=750rpm, FR= 0.15mm/min, DOC= 0.2mm and NR= 0.4mm and the highest MRR parameters were: CS= 750 rpm, FR= 0.25 mm/min, DOC= 0.2 mm and NR= 1.2 mm. To analyse and optimize the surface quality of Al 7075, Patel et al. (2020) attempted JAYA algorithm-based optimization and successfully secured best values of indicators such as average roughness-0.64 µm, deviation in circularity-4.34 µm, and deviation in cylindricity- 0.365 µm.

Table 1. Summary of past work on machining of aluminum and its alloys.

S. No.	Al alloy	Researchers	Turning conditions	Method of DoE/optimization	Parameters		Findings	Conclusions
					Input	Response		
1	AA 6063 T6	(Jayaraman, et al., 2014)	Uncoated carbide insert (DCGT 11 T3 04) – dry cutting	Grey relational analysis (Taguchi)	• CS • FR • DOC	• SR • Roundness • MRR	• FR and DOC are prominent factors • Best performance was obtained at CS of 119.22 m/min, FR of 0.05 mm/rev and DOC of 0.15mm	• FR affects machining at 57.365%, DOC at 25.11% and CS at 17.35% • The grey rational grade for experiments is 0.7717 • Percentage error between predicted and experimental values is 4.7%
3	Al 7075	(Rotella, 2019)	Tungsten carbide insert	Grey relational analysis	• CS • FR • DOC • tool nose radius	• Form error-cylindricity error and circulatory error • average SR • MRR	• Increasing the CS, FR, DOC and nose radius increases the MRR • CS and DOC have insignificant effect on the SR, whereas FR and nose radius have significant effect. • FR has the highest % contribution when it comes to circularity error, followed by DOC then nose radius.	• Study yielded an average SR of 0.64µm, a circularity error of 4.34 µm, and a cylindricity error of 0.365µm and a MRR of 28.63mm3/min at optimum parameters of CS 283m/min, FR 0.17 mm/rev, DOC 0.68mm and nose radius 1.2mm • Increasing the DOC and FR increases the MRR and has negative impact on the SR, circularity and cylindricity error
4	AA 6063	(Eapen, et al., 2017)	(CCGT 120408FCK 10-1) AND (CNMG120408 MP TT 5100)		• FR • CS • DOC (constant)	• Chip classification • Chip reduction coefficient	• Chip formation is favourable at both pre cooled and dry environments • The ductility of AA6063 prevents effective chip formation when using the CCGT 120408 FCK10-1 insert.	• Pre cooled conditions favour better SR and yield a better reduction coefficient • Turning with the precooled CNMG 120408 MPTT5100 insert produces a low chip reduction coefficient at low and medium speeds
5	Al 7075	(Rao, et al., 2017)	Coated carbide inserts	Taguchi	• CS • FR • DOC	• Micro hardness • Residual stress • SR	• The CS and DOC have detrimental effect on the surface residual stresses • Micro hardness decreases with the increase in the DOC.	• Residual stress is inversely proportional to the CS • An increase in the DOC results in the increase of residual stresses • Micro hardness is directly proportional to both DOC and CS.

							• 0.72µm was the maximum SR obtained at a CS of 200m/min	• The cutting force increases with the increase in DOC and are not affected by CS at a given DOC.
6	Al 6351 T6	(Ahmed, et al., 2017)	Carbide cutting tool	Taguchi (ANOVA)	• Nose radius • DOC • FR • CS	• SR • MRR	• Best Ra result parameters are: CS=750rpm, FR= 0.15mm/min, DOC= 0.2mm and NR= 0.4mm • Highest MRR parameters: CS= 750rpm, FR= 0.25mm/min, DOC= 0.2mm and NR= 1.2mm	• Order of effectiveness on SR: nose radius, DOC, FR and CS • Order of effectiveness on MRR: DOC, FR, CS and NR • Low depths of cut, higher CS and high FR are good for high productivity
7	Al 7075	(Patel, et al., 2020)	Tungsten carbide inserts	Central compositi on design	• CS • FR • DOC • Tool nose radius	• Cylindricity error • Circularity error • Average SR • MRR	• 7.97% absolute deviations from the principle component analysis and JAYA algorithm • 0.64µm deviation for average roughness • 4.34µm deviation in circularity error • 0.365µm deviation in cylindricity error • 28.63 cm^3/min deviation in MRR	• Low CS was found insignificant for all responses except MRR • A large nose radius reduces SR and is found insignificant for MRR • A nonlinear relationship was found between the nose radius impact and the circularity and cylindricity errors.
8	Al MMC	Devaraj et al. 2021	Textured Tungsten Carbide Under WS_2 solid lubricant		• Texture hole dia • Texture hole depth • Pitch between holes	• Ra • Power consumption • Flank wear	• Solid lubrication was found effective in reducing tool wear, roughness, and power consumption. • Texture parameters significantly affected the responses by influencing machining mechanisms such as chip formation and friction.	
9	Al 6061	Sreejith, 2008	Diamond coated carbide tool		• Cutting speed • Cutting environment (MQL, Dry, Flood)	• Cutting force • Flank wear • Surface roughness Ra	• MQL machining resulted in machinability at par with flood cooling but is the better option.	
10		Faverjon et al.	PCD HSS Carbide		• Cutting environment (dry and MQL) • Tool material	• Friction coefficient	• Lowest coefficient of friction when machining with PCD tool. • MQL results in minimizing the coefficient of friction.	

While turning aluminum metal matrix composite (MMC), Bansal and Upadhyay (2016) found that the presence of hard ceramic particles in the MMC reduces the MRR and cutting speed improves surface finish. Another important work on the machining of aluminum composites conducted by Kannan et al. (2020), highlights the effectiveness of the TOPSIS optimization technique that resulted in significant improvement in machinability indicators i.e. 16% decrease in roughness, a 22% decrease in tool wear, 32% reduction in machining force.
Machado et al. (2022) investigated the turning of Al-Si-Mg alloys. Two varieties of samples i.e. as-cast and heat-treated were examined where the later was found to produce stable machinability due to better microstructure and mechanical properties. Vilches et al. (2021) conducted a study and found tool wear very influential to affect form deviations like cylindricity, especially at high feed rates and cutting speeds. In an interesting study, Pattnaik et al. (2018) found the superiority of polycrystalline diamond (PCD) tool inserts in obtaining the best machinability of aluminum alloys. Saravanakumar et al. (2018) successfully optimized turning parameters and minimized surface roughness and roundness error. Taguchi's robust optimization technique resulted in the minimization of roundness error from 0.089 mm to 0.062 mm and surface roughness from 1.52 µm to 1.16 µm. A recent investigation conducted by Roy et al. (2021) identified the effectiveness of the textured tool in enhancing the machinability of A1100 alloy under a dry environment. Table 1 summarizes some of the important past work conducted on turning aluminum and its alloys.

3. Conclusion

A brief review on machinability of aluminum under the influence of different machining conditions has been reported in this article. Since aluminum is a soft material, therefore it is difficult-to-machine and necessitates novel techniques of machining. Along with novelty, sustainability is also a major concern and has been taken care of by researchers in the form of successful dry and near-dry machining of aluminum. Prolonging the tool life by reducing tool wear is detrimental to the sustainability of the machining process. There are various methods of coating and texturing that have been explored but little work has been done to explore the advances in tooling together with advances in lubrication and cooling systems for aluminum machining. The combination of these techniques for sustainable machining allows room for research which can influence the way in which manufacturers operate. The use of microwave radiation for tool pre-treating before and after texturing presents a huge gap in research which is an important future research avenue.

Nomenclature:

FR:	Feed rate
DOC:	Depth of cut
SR:	Surface roughness
CS:	Cutting speed
NR:	Nose radius
MRR:	Material removal rate

Acknowledgment

This work is based on the research supported by National Research Foundation, South Africa.

References

Ahmed, S., Arora, R., Optimization of turning parameters of Aluminum 6351 T6 using Taguchi decision making technique. International Journal of Data and Network Science, vol. 1, pp. 27-38, 2017.

Bansal, P., Upadhyay, L., Effect of turning parameters on tool wear, surface roughness and material removal rate of alumina reinforced aluminum composite, Procedia Technology, vol. , no. 23, pp. 304-310, 2016.

Eapen, J., Murugappan, S., Arul, S., A study on chip morphology of aluminum alloy 6063 during turning under pre cooled cryogenic and dry environments, Materials Today: Proceedings, vol. 4, pp. 7686-7693, 2017.

Jayaraman, P., Mahesh kumar L., 2014 Multi-response Optimization of Machining Parameters of Turning AA6063 T6 Aluminum Alloy using Grey Relational Analysis in Taguchi Method. Procedia Engineering, 97, 197-204.

Kannan A., Mohan, R., Viswanathan, R., Sivashankar, N., Experimental investigation on surface roughness, tool wear and cutting force in turning of hybrid (Al7075 + SiC + Gr) metal matrix composites, Journal of Materials Research and Technology, vol. 9, no. 6, pp. 16529-16540, 2020.

Machado, P.A.B., Quaresma, J.MD.V., Garcia, A., Santos, C.L.D., Investigation on machinability in turning of as-cast and T6 heat-treated Al-(3, 7, 12%)Si-0.6%Mg alloys, Journal of Manufacturing Processes, vol. 75, pp. 514-526, 2022.

Mário, C., Santos, J., Alisson, R., Machado, Sales, W. F., Marcos, A. S., Barrozo, E., Ezugwu, O., Machining of aluminum alloys: a review. The International Journal of Advanced Manufacturing Technology, vol. 86, pp.3067-3080, 2016.

Okokpujie, I.P., Tartibu, L.K. A mini-review of the behaviour characteristic of machining processes of aluminum alloys, Materials Today Proceedings, vol. 62, pp. 4526-4532, 2022.

Pandi, G., Muthusamy, S., A Review on machining and tribological behaviors of aluminum hybrid composites, Procedia Engineering, vol. 38, pp. 1399-1408, 2012.

Patel, M. G., Lokare, D., Chate, G. R., Par, M.B., Analysis and optimization of surface quality while machining high strength aluminum alloy, Measurement, vol. 152, pp. 107337-107353, 2020.

Pattnaik, S.K., Bhoi, N.K., Padhi, S., Dry machining of aluminum for proper selection of cutting tool: tool performance and tool wear. Int J Adv Manuf Technol, vol. 98, pp. 55–65, 2018.

Qazi, M.I., Abas, M., Khan, R., Saleem, W., Pruncu, C. I., Omair. M., Experimental investigation and multi-response optimization of machinability of AA5005H34 using composite desirability coupled with PCA, Metals. vol. 11, no. 2: 235, 2021.

Rao, K. S., Allamraju, K. V., Effect on micro-hardness and residual stress in CNC turning of Aluminum 7075 alloy, Materials Today: Proceedings, vol. 4, pp. 975-981, 2017.

Rotella, G., Effect of surface integrity induced by machining on high cycle fatigue life of 7075-T6 aluminum alloy, Journal for Manufacturing processes, vol. 41, pp. 83-9, 2019.

Roy, R. S., Dash, S., Mahapatra, T.R., Mishra D., Jaypuria, S., Cutting performance analysis of surface textured tools in dry turning: optimisation of process parameters. E3S Web Conference, vol. 30, art. no. 01164, 2021.

Saravanakumar, A., Karthikeyan, S.C., Dhamotharan, B., Kumar, V. G., Optimization of CNC turning parameters on aluminum alloy 6063 using Taguchi robust design, Materials Today: Proceedings, vol. 5, no. 2, pp. 8290-8298, 2018.

Soren, T. R., Kumar, R., Panigrahi, I., Sahoo, A. K., Panda, A., Das, R. K., Machinability behavior of Aluminum Alloys: A Brief Study. Materials Today Proceedings, vol. 18, no. 7, pp. 5069-5075, 2019.

Stanojkovic, J., Radovanovic, M., Influence Of The Cutting Parameters On Force, Moment And Surface Roughness In The End Milling Of Aluminum 6082-T6. acta Universitatis, Series: Mechanical Engineering, vol. 20, no. 1, 157-165, 2022.

Totten, G.E., MacKenzie D.S., Handbook of Aluminum, Vol. 1 Physical Metallurgy and Processes. CRC Press, 2003.

Vilches, T., Javier, F., Béjar, S. M., Gamboa C. B.,, Fernández, M. H., Hurtado, L. S., Influence of tool wear on form deviations in dry machining of UNS A97075 alloy, Metals, vol. 11, no. 6, art. no. 958, 2021.

Yeganefar, A., Niknam, S.A., Songmene, V., Machinability study of aircraft series aluminum alloys 7075-T6 and 7050-T7451, Transactions of the Canadian Society for Mechanical Engineering, vol. 44, no. 3, pp. 427-439, 2019.

Biographies

RM Magabe is a PhD scholar at the university of Johannesburg. He completed Masters in Mechanical Engineering with specialization in modern machining. His research interests are advanced manufacturing, green machining, and materials engineering. He has published research articles in international journals.

Sujeet Kumar Chaubey is a Postdoctoral Research Fellow (PDRF) in the Department of Mechanical and Industrial Engineering Technology, University of Johannesburg, South Africa. He did Ph.D. in Mechanical Engineering from Indian Institute of Technology Indore (India) in 2018. He did Master of Technology ‘in Manufacturing Systems Engineering and Bachelor of Technology in Mechanical Engineering from Sant Longowal Institute of Engineering and Technology, Longowal (India) and Gautam Buddha Technical University, Lucknow (India), respectively. He also did Diploma in Engineering specialization in Power Plant Engineering from Institute of Engineering and Rural Technology, Prayagraj (India). Dr. Chaubey has great depth of knowledge and understanding of experimental research. He is expertise in the area of Advanced Machining Processes (EDM, WEDM and hybrid machining), Miniature Gears Manufacturing, Gear Engineering, Sustainable Manufacturing and Optimization Techniques.

Kapil Gupta is working as Professor at University of Johannesburg, South Africa. He obtained PhD in Mechanical engineering. He has over ten years of professional experience. He has authored more than eighty research and review articles. He has also authored and edited twenty international books. His area of specialization is advanced manufacturing and modern industrial engineering. He has carried out research projects in lean manufacturing, modern machining, materials engineering. He is holding positions on the editorial board of international journals. He has supervised five doctorate and twelve masters student.