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Machining performance of ceramic tool inserts during dry turning of hardened steel

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Abstract

For effective dry turning of hardened steels, ceramic tool materials have long been utilized as an alternative to conventional tool materials. Therefore, the purpose of the current work is to investigate whether ceramic materials like alumina (Al_2O_3) are suitable for use as tool materials during the dry (without coolant) turning of hardened steels. In addition, while cutting EN 24 hardened steels, the performance of an alumina ceramic tool insert was compared to a commercial tool insert in the current work. On EN 24 steel samples, turning operations were performed utilizing both alumina ceramic tool inserts and commercial carbide tool inserts at different machining parameters such as speed, feed, and depth of cut. The turning performance of both alumina and commercial tool inserts was evaluated at various machining conditions based on abrasive wear (weight loss) of the tool inserts and the surface roughness of EN 24 machined samples. At all machining parameters, it was found that the abrasive wear of ceramic tool inserts was lower than the abrasive wear of commercial tool inserts. It is observed that, the surface roughness of EN 24 machined samples when machined with ceramic tool inserts was a little higher when compared with the surface roughness values of EN 24 machined samples which are machined with the commercial tool insert. The results of the experiment showed that ceramic cutting tools had comparable cutting performance to commercial cutting tools.

Keywords:
Ceramic tool materials;
Commercial tool inserts;
Dry turning;
EN 24 steels;

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INTRODUCTION

Material removal through machining is a major industrial activity, even though there is a significant development in the modern manufacturing world. Machining system mainly composes of cutting tool, work piece and machine tool out of which cutting tool plays a key role in obtaining effective machining operation. Tool materials can be classified into metals, polymers, ceramics and composites. Inserts made of conventional materials like HSS (High speed steels) and cemented carbides were in use since many decades in the manufacturing world because of their cutting capabilities. Even though these materials are robust at normal temperature, during high-speed machining, they did not exhibit sufficient inertness or wear resistance. Also, the scarcity and toxicity studies of EU (European Union) for conventional tool materials are strongly suggesting for the investigation of alternative tool materials in the place of conventional tool materials [1].

Cutting tool material should meet the requirements of high hardness, thermal shock resistance, chemical inertness and wear resistance. Ceramic materials possess high melting point, hardness, oxidation resistance, chemical stability and corrosion resistance when compared with other tool materials [2][3]. Because of these superior characteristics as shown in Figure 1 and Figure 2, ceramic materials have always had potential as cutting tool materials.

Ceramic materials are generally composed by covalent bonds (Si_3N_4, BN), ionic bonds (Al_2O_3, MgO) and mixed bonds of ionic and covalent bond. Silicon nitride, alumina and SiAlON (silicon nitride based) ceramic materials are used for the preparation of cutting tools.

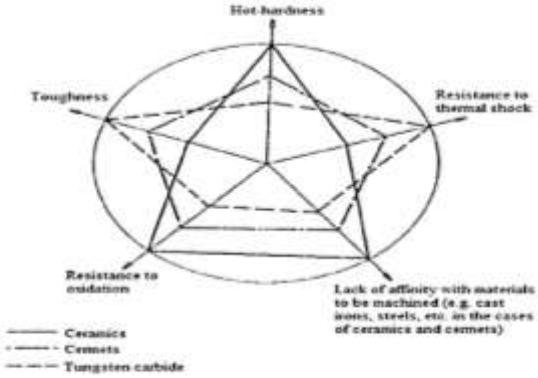


Figure 1. Mechanical properties of different tool materials [2]

Propertis	High speed carbide	C-2 carbide	C-6	TiC	Ceramic
Transverse rupture strengh x 10^3kg/cm^2	35	17.5	17.5	12.25	6.3
Density (g/cm^3)	8.6	14.9	12.7	6.0	3.98
Compressive strength x 10^5kg/cm^3	42	45.5	42.7	31.5	35
Modulus of elasticity x 10^5kg/cm^3	22.4	70	56	42	42
Microhardness (RA)	85	92	91	93	93
Microhardness (knoop 100)	740	1800	1410	-	1780
Melting point (°C)	1300	1400	1400	1400	2000

Figure 2. Properties of different tool materials [3]

Vleugels et.al [4] performed different experiments to investigate the chemical compatibility between iron-based alloys and SiAlON ceramic tool material at a small load of 2.5 MPa (also at elevated temperatures) and measured the interdiffusion in between the two materials. They concluded that at high temperatures (greater than or equal to 1100 °C), SiAlON grains are reacting with iron-based alloys and hence not appropriate for machining iron – based materials.

Zhao Xingzhong et.al [5] prepared pin specimens from hot pressed Si_3N_4 and was used to machine stainless steel (AISI 321) work pieces and also carried out wear tests on a pin-on-disk tribometer, by simulating realistic cutting process. They observed that wear of Si_3N_4 ceramic was increasing with increment of both load and speed. They also concluded that in dry conditions, the wear of Si_3N_4 ceramic is mainly caused by adhesion between the rubbing surfaces. Some other studies also concluded that tool inserts made up of Si_3N_4 based and SiAlON ceramics were exhibiting high wear during machining of hardened steels when compared with the coated SiAlON ceramic inserts [6][7]. Hence, the preparation of the tools with alumina ceramic material was increased as alumina can retain its hardness even at higher temperature and exhibit very less chemical reactivity with steel and other materials when compared with other ceramic materials [8][9].

The plentiful availability of Al_2O_3 (alumina) also facilitated to prepare alumina ceramic tools with economy. All these intrinsic qualities made alumina ceramic to be used to prepare cutting tools even at higher temperatures, which are generated during high-speed machining, that too without being severely affected by deformation which generally dictates tool life. Several authors reported their observations on alumina ceramic material tools. Shunzo Tashima et.al [10] developed a ceramic tool using high-speed centrifugal compaction process from alumina powder with a purity of 99.99 %. They also compared the prepared ceramic tool cutting performance with a commercial alumina (pure) ceramic tool against fracture toughness and wear resistance characteristics. They concluded that proposed pure alumina sintered tool, processed by high-speed centrifugal compaction process, had better fracture resistance and wear resistance characteristics than the commercially available pure alumina ceramic tool during face milling of carbon steel S45C.

Narutaki et.al [11] fabricated ceramic tool with alumina material (99.99%) and performed milling and dry turning operations on S45C carbon steel and grey cast iron and evaluated the performance of alumina tool. Authors observed better performance of the newly fabricated pure Al_2O_3 ceramic tool in terms of both thermal shock resistance and mechanical properties, when compared with the commercially available HIP sintered alumina ceramic tool during milling and dry turning of S45C carbon steels and gray cast iron. During machining, tool materials are exposed to very high stresses, temperatures and vibrations [12]. To withstand at those extreme condition's alumina ceramic of defined grade and charactesticks such as shape and particle size, is to be selected to attain the optimum properties in the final tool material and this specially processed selected grade can only meet the requirement of severe machining conditions [13, 14]. While, high density and finer grain size are the major criteria for the successful performance of the Al_2O_3 ceramic material tool, it is also vital to carry the fabrication process using an effective sintering technique [15].

Dry machining is becoming increasingly popular as it requires no cutting fluid during machining and thus it is considered as the cleanest, safest and economical manufacturing technique [16-21]. Dry machining especially eliminates harmful effects of coolant fluids and cost of disposal, cleaning and filtration of coolants there by reducing overall machining costs [22]. In dry machining, the machining constituents like cutting tool material, work piece material also machining process parameters essentially be considered very carefully for effective machining operation. Materials like cemented carbides, ceramics and cubic boron nitride are most suitable for the case of dry machining [23].

Hence in the present investigation, microwave sintered alumina ceramic (with a purity of 99.95%) tool inserts are used for dry machining EN 24 hardened steel and compared its machining performance with commercial carbide tool inserts in terms of weight loss of the inserts during machining and surface roughness.

METHOD

Pure alumina tool inserts according to standard SNGN 120404 are prepared initially from pure alumina powder using a hydraulic press under a compression load of 6 T using tungsten die. The sintered samples were then sintered using microwave sintering technique (shown in Figure 3 (a)) at 1500^{0}C [24].

The commercial tool used in the present work was carbide tool insert (shown in Figure 3 (b)). Turning operations (Experimental set up was shown in Figure 4) are carried out on EN 24 steel samples by varying machining parameters (shown in Table 1) like feed, cutting speed and depth of cut by using both alumina ceramic tool insert and commercial tool insert for a duration of 5 minutes without using any coolant (dry machining).

The machining performance of the cutting tool inserts were measured by observing wear of the cutting tool inserts and surface roughness of the machined EN 24 sample surfaces. Weight loss (wear) of the tool inserts is computed as shown in (1) by measuring the weights of the cutting tool inserts using a weighing machine, as shown in Figure 5, before and after of each machining operation.

$$\text{Weight Loss (wear)of the tool inserts / min} = \frac{(W_f - W_{i})}{Total\ machining\ time\ (minute)} \qquad (1)$$

Where W_i is an initial weight of tool inserts and W_f is a final weight of tool inserts (after machining)

(a) (b)

Figure 3. Tool Inserts.
(a) pure alumina tool insert (b) Carbide Tool Inserts

Figure 4. Experimental Setup

Table 1. Machining Parameters

Machining Parameter	**Levels of Variation**
Speed	100, 300 and 500 rpm
Feed	0.3, 0.5 and 0.8 mm/rev
Depth of Cut (DOC)	0.1, 0.3 and 0.5 mm

Figure 5. Electronic Weighing Machine

Figure 6. Surface Roughness Tester (SJ-210)

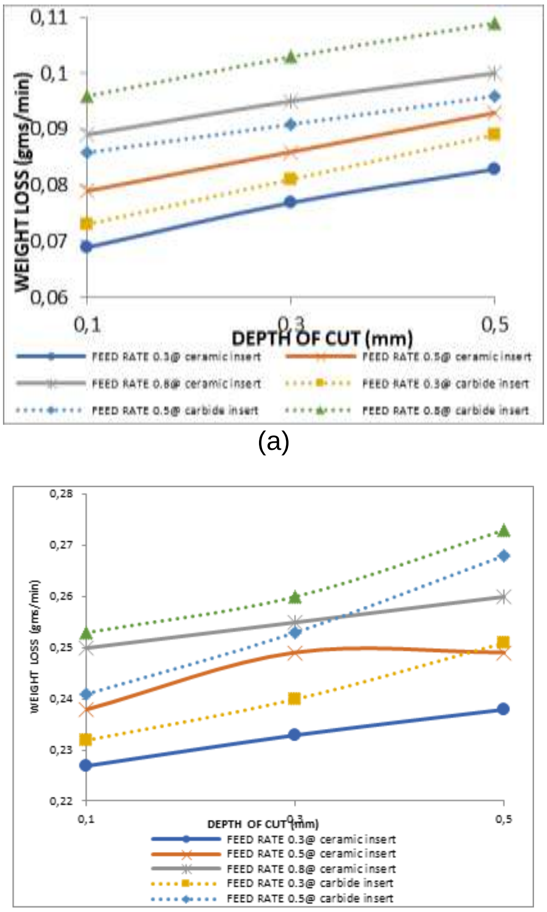
Surface roughness of the EN 24 sample surfaces which are machined by both alumina tool and commercial tool insert are measured with the help of a surface roughness tester, as shown in Figure 6, using SURF TEST SJ-210. The obtained values of wear and surface roughness at different machining conditions during machining with both tool inserts are presented in Table 2 and graphical results are displayed in Figure 7.

Table 2: The obtained values at different machining conditions for both tool inserts

		EN24 at 100RPM (Alumina Ceramic tool) insert		**EN24 at 100RPM (Commercial tool) insert**	
Feed (mm/rev)	**Depth of cut(mm)**	**Weight Loss (gram/min)**	**Surface Roughness (microns)**	**Weight Loss (gram/min)**	**Surface Roughness (microns)**
	0.1	0.069	6.36	0.073	5.40
0.3	0.3	0.077	6.40	0.081	5.45
	0.5	0.083	6.60	0.089	5.60
	0.1	0.079	6.40	0.086	5.50
0.5	0.3	0.086	6.58	0.091	5.52
	0.5	0.093	6.70	0.096	5.78
	0.1	0.089	6.43	0.096	5.56
0.8	0.3	0.095	6.60	0.103	5.67
	0.5	0.100	6.89	0.109	5.80

		EN24 at 100RPM (Alumina Ceramic tool) insert		**EN24 at 100RPM (Commercial tool) insert**	
Feed (mm/rev)	**Depth of cut (mm)**	**Weight Loss (gram/min)**	**Surface Roughness (microns)**	**Weight Loss (gram/min)**	**Surface Roughness (microns)**
	0.1	0.189	6.12	0.101	5.28
0.3	0.3	0.103	6.21	0.106	5.01
	0.5	0.109	6.50	0.128	5.30
	0.1	0.100	6.20	0.108	5.42
0.5	0.3	0.152	6.38	0.169	5.29
	0.5	0.152	6.61	0.160	5.50
	0.1	0.185	6.30	0.198	5.53
0.8	0.3	0.210	6.67	0.220	5.86
	0.5	0.210	6.50	0.229	5.76

		EN24 at 100RPM (Alumina Ceramic tool) insert		EN24 at 100RPM (Commercial tool) insert	
Feed (mm/rev)	**Depth of cut (mm)**	**Weight Loss (gram/min)**	**Surface Roughness (microns)**	**Weight Loss (gram/min)**	**Surface Roughness (microns)**
0.3	0.1	0.227	6.01	0.232	5.31
	0.3	0.233	6.11	0.240	5.20
	0.5	0.238	6.42	0.251	5.10
0.5	0.1	0.238	6.06	0.241	5.36
	0.3	0.249	6.28	0.253	5.21
	0.5	0.249	6.46	0.268	5.32
0.8	0.1	0.250	6.27	0.253	5.46
	0.3	0.255	6.30	0.260	5.30
	0.5	0.260	6.50	0.273	5.50



(a)

(b)

Figure 7. Wear in Alumina ceramic and commercial tool inserts during turning on EN 24 hardened steel samples: (a) 100 rpm speed and (b) 500 rpm speed

From the Figure 7 it was identified that, wear in both the inserts was increasing with the increasing speed, feed and depth of cut during machining EN 24 hardened samples. It is observed that, the increase in wear was more for both inserts with the increase in the speed, when compared with the rate of increase of wear during increase of feed and depth of cut. This may be due to the increased rubbing action between tool insert and work sample with increased speed, which augmented the friction. This might result generation of more heat between the tool insert and work piece and amplified the material loss particularly at higher speeds.

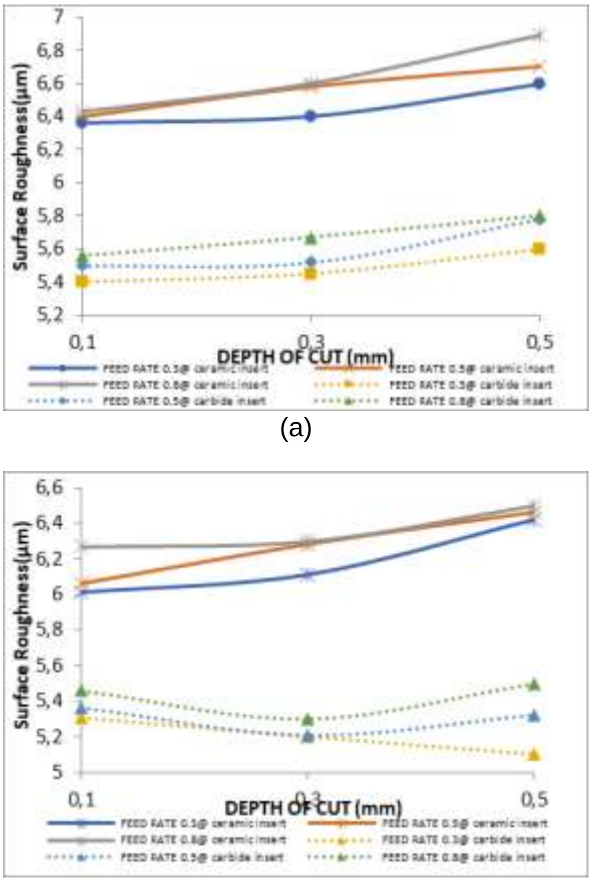
Furthermore, during machining, when compared with the depth of cut, the feed rate was seemed to show much influence on wear (weight loss) of the tool inserts at fixed speed levels. At all machining conditions, wear in alumina tool inserts was observed to be less than the wear of commercial tool inserts during machining of EN 24 steel samples. The low wear (weight loss) of alumina cutting tools can be attributed to high hardness, melting point and chemical stability of alumina ceramic material. Because of these superior characteristics of alumina, ceramic tool inserts made of alumina might have shown higher wear resistance i.e., less wear during turning operation even at higher speed, feed and depth of cut when compared with wear of commercial tool inserts.

From the Figure 8, it was observed that, surface roughness values of EN 24 hardened steel samples machined with alumina tool insert was a bit high when compared with surface roughness values of steel samples machined with commercial tool inserts at same machining conditions. This high surface roughness values in steel samples machined with alumina tool inserts can be attributed to high hardness of alumina ceramic material. This characteristic of alumina, might made the tool inserts to work with grater cutting force during machining of samples which contribute more surface roughness to machined samples.

It was also identified that with the increased speed during machining, surface roughness of EN 24 steel samples were identified to be decreased irrespective of type of insert used for machining. But with the increasing feed rate (at constant speed and depth of cut), surface roughness values for EN 24 machined surfaces were observed to be in the increasing trend, during machining with both the inserts. The influence of depth of cut on surface roughness values is seems to be minimal when compared with the speed and feed rate.

RESULTS AND DISCUSSION

The percentage change in the wear (weight loss) of both the inserts and generated surface roughness on EN 24 machined samples during machining with both the inserts are computed and analyzed for the lower (100 rpm speed, 0.3 mm/rev feed, 0.1 mm DOC) and higher (500 rpm speed, 0.8 mm/rev, 0.5 mm DOC) machining conditions and are presented in the following Table 3.



(a)

(b)

Figure 8. Surface roughness of EN 24 hardened steel samples
(a) 100 rpm speed and (b) 500 rpm speed

Table 3. Percentage variation

Machining conditions			Weight loss (Wear) of tool insert (grams/min)			Surface roughness (microns)		
Speed (rpm)	**Feed (mm/rev)**	**DOC (mm)**	**Alumina ceramic insert**	**Commercial tool inserts**	**Change (%)**	**Alumina ceramic insert**	**Commercial carbide tool Inserts**	**Change (%)**
100	0.3	0.1	0.069	0.073	5.79	6.36	5.40	-15.09
500	0.8	0.5	0.260	0.273	5.00	6.50	5.50	-15.38

From the Table 3, it is observed that the wear of alumina tool insets was less than the wear of commercial tool inserts by 5.79% and 5% at lower and higher machining conditions respectively. The surface roughness values yielded by alumina inserts on EN 24 samples was 15.09% and 15.38% higher than the surface roughness values yielded by commercial tool inserts at the at lower and higher conditions of machining respectively

CONCLUSION

The following conclusions have been drawn after analyzing the results obtained through experimentation.

1. The alumina ceramic tool inserts have shown less wear (weight loss) when compared to commercial tool inserts during machining of EN 24 samples at all machining conditions.
2. Surface roughness of machined EN 24 hardened steel samples yielded by alumina tool insert was observed to be little higher than that of the surface roughness yielded by commercial tool inserts during machining at all machining conditions.
3. Hence, it can be concluded that alumina ceramic tool inserts can be employed for dry machining of EN 24 hardened steels as are observed to be competing with the commercial tool inserts in performance.

Alumina is the main raw material of ceramic cutting tool and is very rich in nature resources. This abundance significantly reduces the production cost of tools made with ceramics like alumina and can have a broad application prospect. Also, when compared with hard alloy, alumina ceramic material greatly saves important tool materials like tungsten and cobalt, as they getting scarce in the recent times. However, it's usage is limited in tool material applications as it exhibits low tensile strength and low fracture toughness. Fabrication route and incorporation of secondary material in the alumina matrix may improve these properties [25, 26, 27]. Hence in future, the improved alumina ceramic tool material may show a greater influence in the machining process of mass productions as the alumina ceramic material is environment friendly and is exhibiting less wear during dry machining than commercial tool inserts.

REFERENCES

[1] A. Rizzo, S. Goel, M. L. Grilli, R. Iglesias, L. Jaworska, V. Lapkovskis, P. Novak, B. O. Postolnyi, D. Valerini, "The Critical Raw Materials in Cutting Tools for Machining Applications: A Review", *Materials*, vol. 13, no. 6, pp. 1377, 2020, doi: 10.3390/ ma13061377.

[2] S. N. Grigoriev , S. V. Fedorov and K. Hamdy, "Materials, properties, manufacturing methods and cutting performance of innovative ceramic cutting tools a review", *Manufacturing Review*, vol. 6, no. 19, 2019, doi: 10.1051/mfreview/2019016.

[3] Smith, G.T., *Cutting Tool Materials: Cutting Tool Technology*, Springer, London, 2008.

[4] J. Vleugels, T. Laoui, K. Vercammen, J.P. Celis, O. Van Der Biest, "Chemical interaction between a sialon cutting tool and iron-based alloys", *Materials Science and Engineering: A*, vol. 187, no. 2, pp. 177-182, 1994, doi: 10.1016/0921-5093(94)90345-X.

[5] Z. Xingzhong, L. Jiajun*, Z. Baoliang, M. Hezhou, L. Zhenbi, "Wear behavior of Si3N4 ceramic cutting tool material against stainless steel in dry and water-lubricated conditions", *Ceramics International*, vol. 25, no. 4, pp. 309-315, 1999, doi: 10.1016/S0272-8842(98)00040-6.

[6] J. Liu, C. Ma, G. Tu, Y. Long, "Cutting performance and wear mechanism of Sialon ceramic cutting inserts with TiCN coating", *Surface and Coatings Technology*, vol. 307, no. 2, pp. 146-150, 2016, doi: 10.1016/j.ceramint.2019.09.134.

[7] J. Vleugels, "Fabrication, Wear and Performance of Ceramic Cutting Tools", *Advances in Science and Technology*, vol. 45, no. 2, pp. 1778-1786, 2006, doi: 10.4028/www.scientific.net/AST.45.1776.

[8] A. Hosseini and H. A. Kishawy, "Cutting Tool Materials and Tool Wear", Chapter 2, *Machining of Titanium alloys, Materials Forming, Machining and Tribology*, Springer, doi: 10.1007/978-3-662-43902-9_2.

[9] J. R. Davis, *Tool Materials*, ASM Specialty Handbook 06506g, 1995.

[10] S. Tashima, Y. Yamane, H. Kuroki, N. Narutaki, “Cutting Performance of High Purity Alumina Ceramic Tools formed by a High-speed Centrifugal Compaction Process”, *Journal of Materials Processing Technology*, vol. 62, no. 4, pp. 431-434, 1996, doi: 10.1016/S0924-0136(96)02448-X.

[11] N. Narutaki (Z), Y. Yamane, S. Tashima, H. Kuroki, “A New Advanced Ceramic for Dry Machining”, *Annals of the CIRP*, vol. 46, no. 1, pp. 43-48, 1997, doi: 10.1016/S0007-8506(07)60772-0.

[12] P. Guimaraes B.M, S. Fernandes C.M, A. de Figueiredo D, ″Cutting temperature measurement and prediction in machining processes: comprehensive review and future perspectives”, *The International Journal of Advanced Manufacturing Technology*, vol. 120, no. 5-6, pp. 2849-2878, 2022, doi: 10.1007/s00170-022-08957-z.

[13] M. Varga, R. Grundtner, M. Maj, F. Tatzgern, K. Alessio, “Impact-abrasive wear resistance of high alumina ceramics and ZTA”, *Wear*, vol. 522, pp. 204700, 2023, doi: 10.1016/j.wear.2023.204700.

[14] C. Piconi, “Alumina”, *Comprehensive Biomaterials*, vol. 1, pp. 73-94, 2011.

[15] P. Ramakrishnan, “Alumina Cutting Tools”, *Transactions of the Indian Ceramic Society*, vol. 31, no. 4, pp. 106-112, 2014.

[16] P.S Sreejith, B.K.A Ngoi, “Dry machining: Machining of the future”, *Journal of Materials Processing Technology*, vol. 101, no. 1-3, pp. 287-291, 2000, doi: 10.1016/S0924-0136(00)00445-3 .

[17] S. Debnath, M. Mohan Reddy, A. Pramanik , “Dry and Near-Dry Machining Techniques for Green Manufacturing”, *Innovations in Manufacturing for Sustainability*, pp. 1-27, 2018, doi: 10.1007/978-3-030-03276-0_1.

[18] Y. Singh Goindi, P. Sarkar, “Dry machining: A step towards sustainable machining – Challenges and future directions, “*Journal of Cleaner Production*, vol. 165, pp. 1557-1571, 2017, doi: 10.1016/j.jclepro.2017.07. 235.

[19] S. Bayraktar, “Dry cutting: a sustainable machining technology”, *Sustainable Manufacturing*, pp. 231-257, 2021, 10.1016/B978-0-12-818115-7.00004-3.

[20] J. Haider, M.S.J. Hashmi, “Health and Environmental Impacts in Metal Machining Processes”, *Comprehensive Materials Processing*, pp. 7-33, , 2014, doi: 10.1016/B978-0-08-096532-1.00804-9.

[21] M.V.R. Durga Prasad, T. Malyadri, S.N.S. Sai Hari, “Sensitivity analysis for process parameters influencing surface roughness of hardened steel in dry machining process”, *Materials Today: Proceedings*, vol. 26, Part 2, pp. 2521-2524, 2020, doi: 10.1016/j.matpr.2020.02.536 .

[22] V. Kharka, N. Kumar Jain, “Achieving sustainability in machining of cylindrical gears”, *Sustainable Manufacturing*, pp. 391-426, 2021, doi: 10.1016/B978-0-12-818115-7.00002-X.

[23] S. Debnath, M. Anwar, A. Pramanik, A. Kumar Basak, “Nanofluid-minimum quantity lubrication system in machining: towards clean manufacturing”, *Sustainable Manufacturing*, , pp. 109-135, 2021, doi: 10.1016/B978-0-12-818115-7.00014-6.

[24] K. I. Vishnu Vandana, K. N. S. Suman, “Finite element modelling and experimental investigation on mechanical properties and micro structural studies of alumina-graphene composites”, *New Materials, Compounds and Applications*, vol. 5, no. 3 pp. 156-170, 2021, doi: 10.1016/j.tca.2016.06.016.

[25] J. Zhao Feng Y, C. NN, Chen FY, C. J, Zhang XB, P. XB, Tu J, O. XP, “Fabrication and Mechanical Properties of Alumina–CNTs Composites”, *Applied Mechanics and Materials*, vol. 66, pp. 1390-1396, 2011, doi: 10.4028/www.scientific.net/amm.66-68.1390

[26] H. Wahyudi, S. E. Pratiwi, A. A. Supriyanto, D. P. B. Aji, “The influence of heat rate and austenitization temperature on microstructure and hardness of Hadfield steel,” *SINERGI*, vol. 27, no. 2, pp. 241-248, 2027, doi: 10.22441/sinergi.2023.2.012

[27] Y. P. Asmara,” Simulation of CO2 Corrosion of Carbon Steel in High Pressure and High Temperature Environment (HPHT),” *Journal of Integrated and Advanced Engineering (JIAE)*, vol. 2, no. 1, pp. 63-70, 2022, doi: 10.51662/jiae.v2i1.41

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