A review on hybrid nanofluid: current research and sustainable development for turning operation

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Abstract: In turning operation, the cutting fluid performs the important function of lubrication as well as cooling at cutting tool-work material machining zone. In the view of sustainable development for the machining domain like turning operation, nanofluid as a cutting fluid provides significant results as compared to conventional cutting fluids. Nanofluid appeared as a capable cutting fluid due to its effective thermo-physical properties. In current work, various types of the hybrid nanofluids utilised as cutting fluid for machining operations were studied. Also, the thermo-physcial properties, and preparation methodologies of hybrid nanofluid were presented. For the appropriate hybridisation of different nanoparticles, the methods for synthesis and characterisation are presented briefly. The comprehensive review for the application of monotype and hybrid nanofluid in turning operation is stated with noticeable facts. The review study concluded that hybrid nanofluids are significant as compared to monotype nanofluids for turning operation. The utilisation of hybrid nanofluid in turning operation resulted into one of the important sustainable developments.

Keywords: hybrid nanofluid; sustainable development; cutting fluid; turning operation.

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1 Introduction

In sustainable metal cutting industry, excess amount of heat is generated at cutting tool and workpiece interface. Additionally, during high speed machining under dry environment, required surface quality and life of tool cannot be reached due to generation of high heat in machining zone may disturb the various properties of tools. This phenomenon of excess heat generation may convert into cutting tool failure (Upadhyay et al., 2013). To carry out high speed metal cutting process, cutting fluids are required in bulk quantity and plays important role by cooling the metal cutting zone. The traditional methodology of cooling system functions the cooling up to certain level on the other hand, the bulk utilisation of the traditional cutting fluid spoils the ecological conditions and may be dangerous for shop floor people. As per the guidelines of National Institute for Occupational Safety and Health (NISOH – USA), the recommended range for exposure of cutting fluid is 0.5 mg/m^3. Also, Occupational Safety Health Administration (OSHA – USA) suggested cutting fluid exposure range is 5 mg/m^3. In the USA, 1.2 million shop floor people were exposed to 100 million gallons of cutting fluid every year. The various types of skin problems, lung disorders, cancer, and noxiousness were detected among shop flood people in metal cutting industries (Boubekri et al., 2010). Hence to restrict the bulk and continuous utilisation of cutting fluids, new promising techniques came into picture in which very less amount of cutting fluid required. This technique is known as minimum quantity lubrication technique or semi-dry machining or near dry machining (Kurgin et al., 2014). Nearly 10,000 times, a smaller quantity of cutting fluid consumed as compared to traditional cooling methodology during metal cutting process (Babu et al., 2017; Musavi et al., 2019). The general range for cutting fluid utilisation in MQL system is 10 to 300 ml/hr for any metal cutting operation (Sakharkar and Pawade, 2018). In MQL, cutting fluid is directed at cutting zone under defined pressure to achieve better penetration into cutting zone, so that the purpose of cooling and lubrication of cutting zone resolve properly (Sharma et al., 2018). Eminent researchers reported valuable research work and observed that with the effective utilisation of MQL during metal cutting process of various material, output parameters such as cutting zone temperature, tool wear, cutting force and surface roughness significantly affected (Hadad and Sadeghi, 2013; Makadia and Nanavati, 2013; Sharma et al., 2015a; Musavi et al., 2018; Mia et al., 2018; Gupta et al., 2020). The cost contribution of cutting fluids observed between 5% to 20% towards product production cost (Carou et al., 2014; Chetan et al., 2015; Sharma et al., 2016a; Gajrani et al., 2017; Khan and Maity, 2018).

With noteworthy facts, MQL became economically viable alternate option to traditional method of cooling system for any machining operation. Hence, MQL minimised production cost as well as ecological threats (Junankar et al., 2019a). Also, the MQL has capability to improve the cutting fluid thermal stability and lubrication ability over traditional cooling system (Gaitonde et al., 2008). Nowadays, to increase the effectiveness of MQL system, the new term combined with it, known as 'nanofluid'. Due to utilisation of the nanometre in sized particles, the thermophyscial properties of cutting fluid can be improved along with machining performance (Moraveji et al., 2011). Nanofluids are mixture of particle having sized 1-100nm and base fluid. The various types of nanoparticles are metal, non-metal, carbon-based tubes, oxides, etc. In 1995, Dr. Choi first presented the term 'nanofluid' in the science and technology domain (Junankar et al., 2019b). During prior research work, monotype of nanofluid utilised as cutting fluid during machining process and output parameters significantly affected. Numerous research studies conducted by investigators and concluded that machining process performance can be enhanced on the basis of benefits of nanofluids such as better stability of cutting fluid due to 'Brownian motion', excellent tribological state, good wettability along with thermal conductivity and maximum heat transfer ratio (Musavi et al., 2019). The nanoparticles spreads over the rubbed surface can enhance the tribological characteristics of cutting fluid resulted into effective decline in friction and rate of wear (Chang et al., 2010). The rolling effect advocated by nanoparticles at cutting tool-workpiece interface decreases friction and enhances the quality of product surface (Ali et al., 2017b). Also, the noticeable enhancement in load bearing ability of sliding parts with the addition of nanoparticles into cutting fluid. It is resulted into increment in thermo-physical properties of cutting fluid and decrement of cutting forces, temperature, wear rate (Sharma et al., 2015b). Due to increment of nanoparticle concentration, thermal conductivity of cutting fluid improved and directly promoted the rate of heat transfer ability of the cutting fluid (Tiwari et al., 2012). The lubrication ability of nanofluid increased by using ball bearing effect, tribo-film generation, mending and polishing effect. The above reported significant facts made monotype of nanofluid as an excellent type of cutting fluid and shown significant results in the domain of metal cutting industries (Gupta et al., 2016). The combination of monotype nanofluid and MQL resulted remarkably, the associated cost with the nanofluid is higher than traditional cutting fluid, but the nanofluid-MQL system impacted on the cost involvement. Because, the nanofluid directed at cutting zone via MQL system, very less amount of nanoparticles sprayed effectively at target zone. Therefore, the minimum utilisation of nanoparticles promoted by MQL, resulted into the noteworthy reduction in cost for nanoparticle enriched cutting fluid. In recent times, to increase the thermophysical properties of nanofluid, two dissimilar nanoparticles impregnated in base fluid due to which novel type of nanofluid formed, named as 'hybrid nanofluid'. A hybrid nanofluid which cartels properties like physical as well as chemical in parallel way and offers excellent properties in standardised phase. Excellent thermophysical properties can be exhibit in hybrid nanofluid that does not observed in monotype of nanofluid. Therefore, higher thermal conductivity reported as equalled to monotype of nanofluid (Kumar and Arasu, 2017).

Many eminent investigators have presented number of experimental studies on effect of monotype of nanofluid with MQL in turning operation. However, the comprehensive and comparative literature is not available on the effect of hybrid nanofluid with MQL in turning operation. Hence, the key objective of present study is to reviewing the hybrid nanofluid research studies, to understand the innovative concept of hybrid nanofluid which can be used as a smart resource for sustainable development in the domain of the machining such as turning operation. To accomplish the overall review study, following objectives were focussed:

1 properties and preparation methodologies of hybrid nanofluid
2 methods for synthesis and characterisation of hybrid nanoparticles
3 application of monotype nanofluid in turning operation
4 application of hybrid nanofluid in turning operation.

Finally, the research paper is structured as: Section 2 is concept of hybrid nanofluid along with properties and preparation methodologies, Section 3 is methods of synthesis and characterisation of hybrid nanoparticles, Section 4 is application of monotype nanofluid in turning operation, Section 5 is application of hybrid nanofluid in turning operation, and Section 6 is conclusions and future scope of research work.

2 Hybrid nanofluid

Prior research work stated as a hybrid nanofluid is the mixture of two nanoparticles mixed with base fluid. The benefit in improvement in rate of heat transfer is due to their synergistic effect as equalled to monotype of nanofluid. Also, hybrid nanofluid provided excellent thermal features as equalled with monotype of nanofluid and base fluid separately. The various parameters are responsible for property enhancement like selection of base fluid, size of nanoparticle, viscosity, temperature of fluid, stability, method of preparation, purity, dispersion ability, shape and size of particles that marched to tuneful combination of the nanofluid (Sidik et al., 2017).

2.1 Properties of hybrid nanofluid

Numerous investigators reported few main thermophysical properties which help to carry out appropriate characterisation of hybrid nanofluid. Mostly, researchers were focused on thermal conductivity, density, viscosity, dielectric strength of hybrid nanofluid. From the prior research work, the summary for thermophysical properties of hybrid nanofluid is shown in Table 1.

2.2 Preparation methodologies

Preparation of nanofluid is one of the critical step on which the stability of the prepared nanofluid depends. In this section, preparation methodologies for nanofluids are summarised. The conventional approaches for hybrid nanofluid preparation are two, by dispersion of individual nanoparticles or by synthesis. To achieve the uniformity and stability in dispersion, sonication can be best option along with surfactant addition in a proper manner. Prior research work stated as – one step and two step methods are available for hybrid nanofluid preparation.

Table 1 Summary for thermophysical properties of hybrid nanofluid

References	*Hybrid nanofluid*	*Thermophysical property*
Han et al. (2007)	Hybrid sphere/CNT	Thermal conductivity
Jana et al. (2007)	CNT/Au and CNT/Cu	Thermal conductivity
Ho et al. (2010)	Al_2O_3/PCM	Density, thermal conductivity
Suresh et al. (2011)	Al_2O_3/Cu	Thermal conductivity
Botha et al. (2011)	Ag/silica	Viscosity, dielectric strength and thermal conductivity
Paul et al. (2011)	Al/Zn	Thermal conductivity
Baby et al. (2011b)	Ag/HEG	Thermal conductivity
Baby et al. (2011a)	MWNT/HEG	Thermal conductivity
Baghbanzadeh et al. (2012)	Silica/MWCNT	Thermal conductivity
Nine et al. (2012)	Al_2O_3/MWCNT	Thermal conductivity
Chen et al. (2012)	Ag/MWNT	Thermal conductivity
Aravind and Ramaprabhu (2012)	Graphene/MWNT	Thermal conductivity
Nine et al. (2013)	Cu/Cu_2O	Thermal conductivity
Baby and Ramaprabhu (2013)	Ag/MWNT-HEG	Thermal conductivity
Abbasi et al. (2013)	Al_2O_3/MWCNT	Thermal conductivity
Munkhbayar et al. (2013)	Ag/MWNT	Thermal conductivity
Chen et al. (2014)	Fe_2O_3/MWNT	Thermal conductivity
Batmunkh et al. (2014)	Ag/TiO_2	Thermal conductivity
Sundar et al. (2016a)	Nanodiamond/Fe_3O_4	Viscosity, thermal conductivity
Sarbolookzadeh et al. (2016)	MWCNT-Fe_3O_4/EG	Thermal conductivity
Esfe et al. (2017a)	SWCNT/MgO	Thermal conductivity
Vafaei et al. (2017)	MgO-MWCNTs/EG	Thermal conductivity
Rostamian et al. (2017)	CuO/SWCNT	Thermal conductivity
Esfe et al. (2017b)	MWCNT/SiO_2	Thermal conductivity
Esfe et al. (2017c)	ZnO/MWCNT	Thermal conductivity

2.2.1 One step method

The production of nanoparticle and preparation of nanofluid is completed alongside. Here, synthesis of nanoparticles and their suspension with base fluid is accomplished in one step. It is the most appropriate method to evade oxidation especially for metals having maximum thermal conductivity. Good stability and uniformity in dispersion can be achieved with the help of one step method. The main drawback of one step method is mass and commercial scale production of nanofluids is not possible due high cost involvement (Babu et al., 2017). Very few researchers utilised one step method for the production of hybrid nanofluid (Botha et al., 2011; Munkhbayar et al., 2013; Aberoumand and Jafarimoghaddam, 2018).

2.2.2 Two step method

The production of nanoparticle carried out separately and suspended with base fluid. The preparation of nanoparticles is economical at large-scale. The main problem with this method is agglomeration observed due to cohesive force and Vander Waal force between nanoparticles. The observed agglomeration can be minimised by using proper surfactant in a proper concentration. Other methods to reduce agglomeration are stated in prior research work such as ultrasonic bath and disrupter, magnetic stirrer. Numerous researchers utilised two step method for the production of hybrid nanofluids (Wei et al., 2017; Hamid et al., 2017; Nabil et al., 2017; Qing et al., 2017; Tahat and Benim, 2017; Asadi et al., 2018; Parsian and Akbari, 2018; Esfahani et al., 2018).

3 Synthesis and characterisation of hybrid nanofluid

Researchers reported and utilised various techniques to synthesis hybrid nanofluids. The most preferred synthesis methods are: mechanical alloying, thermo-chemical method, in-situ method, ball milling, chemical vapour deposition, spray pyrolysis, wet chemical, solvo-thermal process, wet ball milling, chemical reduction and hydrogen induced exfoliation method. Similarly, the commonly techniques utilised for characterisation of hybrid nanofluids are: XRD, SEM, TEM, FESEM, FTIR, EDAX, VSM and XPS. Summary for synthesis and characterisation techniques utilised for hybrid nanofluid shown in Table 2 and Table 3, respectively.

Table 2 Summary for synthesis methods for hybrid nanofluid

References	*Hybrid nanofluid*	*Method of synthesis*
Kumar et al. (2016)	Cu/Zn	In-situ
Sundar et al. (2014)	MWCNT/Fe_3O_4	In-situ
Sundar et al. (2015)	CNT/Fe_3O_4	In-situ
Shende and Sundara (2015)	N doped HC	Spray pyrolysis
Nine et al. (2012)	Al_2O_3/MWCNT	Chem. vapour depo.
Aravind and Ramaprabhu (2013)	Graphene/MWCNT	Chem. vapour depo.
Paul et al. (2011)	Al/Zn	Mechanical alloying
Abbasi et al. (2013)	CNT/Al_2O_3	Solvo-thermal
Mechiri et al. (2017)	Cu/Zn	Ball milling
Chen et al. (2012)	Ag/MWNT	Ball milling
Yarmand et al. (2016)	C/graphene oxide	Ball milling
Baghbanzadeh et al. (2012)	Silica/MWCNt	Wet chemical
Nine et al. (2013)	Cu/Cu_2O	Wet ball milling
Baby and Sundara (2011)	Metal oxide/graphene	Hydrogen ind. exf.
Yarmand et al. (2015)	Graphene/Ag	Chemical reduction
Suresh et al. (2011)	Al_2O_3/Cu	Thermo chemical
Suresh et al. (2012)	Al_2O_3/Cu	Thermo chemical

Table 3 Summary for characterisation methods for hybrid nanofluid

References	*Hybrid nanofluid*	*Method of characterisation*
Esfe et al. (2017b)	SiO_2/MWCNT	XRD
Esfe et al. (2017c)	ZnO/MWCNT	XRD, TEM
Esfe et al. (2017d)	SWCNT/ZnO	XRD, TEM
Esfe et al. (2017a)	SWCNT/MgO	XRD
Rostamian et al. (2017)	CuO/SWCNT	XRD
Sundar et al. (2015)	CNT/Fe_3O_4	XRD, SEM, TEM
Shende and Sundara (2015)	N doped HC	XRD, TEM, XPS
Paul et al. (2011)	Al/Zn	SEM, TEM
Sundar et al. (2016b)	Nanodiamond/Fe_3O_4	SEM, TEM, FTIR
Munkhbayar et al. (2013)	Ag/MWCNT	SEM, TEM
Batmunkh et al. (2014)	TiO_2/Ag	SEM
Shahsavar et al. (2015)	Fe/CNT	XRD, SEM, TEM
Shahsavar et al. (2015)	Fe/CNT	XRD, SEM, TEM
Sundar et al. (2018)	Nanodiamond/Ni	XRD,TEM, VSM
Sundar et al. (2017)	Graphene oxide/Co_3O_4	XRD, TEM, VSM
Madhesh et al. (2014)	Cu/Ti	XRD, FESEM, EDAX
Madhesh et al. (2014)	Cu/TiO_2	XRD, FESEM, EDAX
Shirazi et al. (2015)	Carbon/graphene	XPS
Sundar et al. (2016a)	ND/Co_3O_4	XPS
Thakur et al. (2019a)	Al_2O_3/CuO	TEM, SEM

4 Application of monotype nanofluid in turning operation

Machining sector includes numerous operations such as milling, drilling, turning and grinding which are used for product manufacturing since long time. Among these operations, turning is the most popular and commonly used operation in which by using single point cutting tool (SPCT) the surface of cylindrical workpiece removes to convert it into desired shape and size. The scrap material is known as chips and it slips on the face of SPCT. Turning operation extensively used for production of parts such as axles, shafts, knobs, screw, pins, bolts, etc. and carried out on turning machine tools. To enhance the output performance of turning operation in the view of quality, awareness related to consumption of cutting fluid with respect to ecological conditions is extremely important. In past decade, various types cutting fluid have been utilised and among all the types, nanofluids found to be most effective one by considering machining input parameters. In most of the prior experimental work, the mode of supply of nanofluid as a cutting fluid was MQL system during turning operation. In this section, the effect of monotype nanofluid with MQL in turning operation of different work materials is discussed and summary present in Table 3. Researcher performed the turning of Inconel 718 work material under the Al_2O_3 nanofluid and observed the reduction in tool wear and coefficient of friction due to wettability of characteristics of nanofluid (Behera et al., 2017). The turning of AISI 4340 steel were performed by utilising MWCNT nanofluid and the substantial decrement reported surface roughness, cutting zone temperature, tool wear and cutting force (Patole and Kulkarni, 2018). MoS_2 nanofluid used as cutting fluid during AISI 1040 steel turning resulted into minimisation of output variables like roughness, wear rate, temperature and cutting force (Pasam et al., 2018). Again, AISI 1040 steel turning performed by supplying TiO_2 nanofluid through MQL system, the effective decrement reported in response variables by investigator (Sharma et al., 2016b). Tool wear rate, roughness and machining zone temperature reduced with Al_2O_3 nanofluid-MQL during turning of Inconel 600 work material (Vasu and Pradeep, 2011). Also, cutting force, roughness and cutting temperature minimisation noticed by researcher in steel turning with MQL plus silver nanofluid (Saravanakumar et al., 2014). The investigator reported decline in cutting force and roughness in En31 turning by utilising CNT nanofluid-MQL system (Raju et al., 2017). The experimental work for utilisation of Al_2O_3 nanofluid in AISI 4340 turning operation resulted into significant reduction in response variables (Khandekar et al., 2012). MQL with graphite nanofluid used in AISI 1040 steel turning and minimisation of output machining parameters such as surface roughness, wear rate of tool and temperature reported (Amrita et al., 2014). Power consumption and tool wear effectively minimised during titanium alloy turning under Al_2O_3 nanofluid cutting fluid (Ali et al., 2017a). Investigator performed titanium turning with CNT nanofluid shown noticeable results on response parameters (Hegab et al., 2018a). Again, the noteworthy outcomes reported for surface roughness during titanium-based alloy turning under MWCNT nanofluid (Hegab et al., 2018b). AISI 1045 steel turning performed by researchers with graphite nanofluid shown marginally excellent results for minimisation of cutting zone temperature and force (Su et al., 2015). Under the cooling environment of Al_2O_3 monotype-nanofluid, the decrement in product roughness, wear rate and cutting force noted during AISI 1040 steel turning operation (Sharma et al., 2016a). H11 steel turning performed with Cu nanofluid resulted into reduction in surface roughness and tool wear (Ganesan et al., 2018). MoS_2 nanofluid utilised for AISI 1040 steel turning, the excellent results were observed by investigator substantial reduction in surface roughness and machining temperature (Rapeti et al., 2018). From the above stated prior research work, most of eminent investigators reported decrease in roughness and cutting force under monotype of nanofluid. Due to high area to volume ratio of nanoparticles, the coated layer generated and this promotes the minimisation of friction between work material and cutting tool (Sayuti et al., 2014). Also, during turning operation the generated micro cracks were filled by nano shaped particles and noticeable reduction in surface roughness observed (Nehme et al., 2010). Few investigators stated appreciable minimisation of cutting zone temperature due to which life of cutting tool increased during turning operation. Nanoparticle possesses excellent thermal conductivity, the enhancement of cutting fluid thermal conductivity possible by addition of nanoparticles. This leads to the increment in heat transfer rate of the cutting fluid. The maximum heat extraction from cutting zone achievable by using nanofluid and this affects cutting zone temperature directly (Singh et al., 2017). Summary of prior research work related to utilisation of monotype nanofluid in turning is summarised in Table 4.

Table 4 Summary of prior research work related to utilisation of monotype nanofluid in turning

References	*Workpiece*	*Monotype nanofluid*	*Mode of supply*		*Output variables*
Behera et al. (2017)	Inconel 718	Al_2O_3	MQL	1	Tool wear
Patole and Kulkarni (2018)	AISI 4340	MWCNT	MQL	1	Cutting force
				2	Surface roughness
				3	Tool wear
				4	Cutting temp.
Pasam et al. (2018)	AISI 1040	MoS_2	MQL	1	Cutting force
				2	Surface roughness
				3	Tool wear
				4	Cutting temp.
Sharma et al. (2016b)	AISI 1040	TiO_2	MQL	1	Cutting force
				2	Surface roughness
				3	Tool wear
				4	Cutting temp.
Vasu and Pradeep (2011)	Inconel 600	Al_2O_3	MQL	1	Surface roughness
				2	Tool wear
				3	Cutting temp.
Saravanakumar et al. (2014)	Steel	Silver	MQL	1	Cutting force
				2	Surface roughness
				3	Cutting temp.
Raju et al. (2017)	En31	CNT	MQL	1	Cutting force
				2	Surface roughness
Khandekar et al. (2012)	AISI 4340	Al_2O_3	MQL	1	Cutting force
				2	Surface roughness
				3	Tool wear
Amrita et al. (2014)	AISI 1040	Graphite	MQL	1	Cutting force
				2	Surface roughness
				3	Tool wear
				4	Cutting temp.
Ali et al. (2017a)	Ti-alloy	Al_2O_3	MQL	1	Power consumption
				2	Tool wear
				3	Surface roughness
Hegab et al. (2018a)	Ti-alloy	MWCNT	MQL	1	Power consumption
				2	Tool wear
Hegab et al. (2018b)	Ti-alloy	MWCNT	MQL	1	Surface roughness
Su et al. (2015)	AISI 1045	Graphite	MQL	1	Cutting temp.
				2	Cutting force

Table 4 Summary of prior research work related to utilisation of monotype nanofluid in turning (continued)

References	*Workpiece*	*Monotype nanofluid*	*Mode of supply*		*Output variables*
Sharma et al. (2016a)	AISI 1040	Al_2O_3	MQL	1	Cutting force
				2	Surface roughness
				3	Tool wear
Ganesan et al. (2018)	H11 steel	Cu	MQL	1	Surface roughness
				2	Tool wear
Rapeti et al. (2018)	AISI 1040	MoS_2	MQL	1	Tool life
				2	Surface roughness
				3	Cutting temp.

5 Application of hybrid nanofluid in turning operation

The various eminent researchers carried out the research work on utilisation of monotype of nanofluid during turning of different material. But, the experimental studies related to utilisation of hybrid nanofluid during turning operation are started from last one and half year. In this section, few studies done by eminent researcher are discussed briefly along with all the aspects and summary presented in Table 5.

An investigational study on utilisation of hybrid nanofluid (Al_2O3/MoS_2) and monotype nanofluid (Al_2O_3) for turning of AISI 304 steel (Sharma et al., 2017a). The vegetable oil with distilled water used as a base fluid. Hybrid nanofluid generated by using volumetric ratio 90:10. The utilised concentration for nanofluid is of three types 0.25, 0.75 and 1.25 volume %. As an arithmetic modelling tool, response surface methodology was utilised by investigators. Also, regression models were stated by investigators for output variables such as cutting forces and surface roughness. Under the hybrid nanofluid cooling environment, cutting force and surface roughness significantly reduced as compared to alumina cooling environment (Singh et al., 2017). The investigator reported that utilisation of hybrid nanofluid (Al_2O_3/GnP) and monotype of nanofluid (Al_2O_3) during AISI 304 steel turning operation. Servo cut base fluid is used for nanofluid preparation. Response surface methodology used for process optimisation purpose. The experimental study concluded that the significant reduction found in surface roughness and cutting force under hybrid nanofluid cooling environment. In this investigation, hybrid nanofluid shown excellent results as compared to monotype of nanofluid (Sharma et al., 2017b). The eminent researcher presented the experimental study for comparison between hybrid nanofluid (Al_2O_3/GnP) and monotype of nanofluid (Al_2O_3) during AISI 304 steel turning operation. After DOE and ANOVA, it was found that hybrid nanofluid as coolant shown excellent result by decreasing wear rate and cutting temperature. Due to which, the performance of metal cutting process improved in terms of surface quality and life of cutting tool (Jamil et al., 2019). A research study presented by investigator regarding utilisation of hybrid nanofluid (Al_2O_3/CNT) and compared with cryogenic cooling during the turning of Ti-alloy. The mode of supply of hybrid nanofluid was minimum quantity lubrication. The vegetable oil used as base fluid for nanofluid preparation. Taguchi-base method used to evaluate the machining performance. The surface roughness, cutting force effectively reduced under hybrid nanofluid as compared to cryogenic cooling technique. Only cutting zone temperature significantly reduced under cryogenic cooling environment. Investigator evaluated the performance of Al_2O_3/CuO hybrid nanofluid during En24 steel turning, the noteworthy reduction stated for the roughness, wear rate and cutting zone temperature (Thakur et al., 2019a). Similar kind of minimisation in surface roughness, cutting temperature and cutting force observed under Al_2O_3/CuO hybrid nanofluid MQL cooling condition during En24 steel turning operation (Thakur et al., 2019b). AISI 1040 steel turning performed under MWCNT/MoS_2 hybrid nanofluid MQL cooling environment, the effective decrement in roughness, machining temperature, cutting force and wear rate of tool directly affects life of tool as well as product surface quality (Gugulothu and Pasam, 2020). From the above mentioned prior research work, it can be concluded that very few experimental studies available related to utilisation of hybrid nanofluid during turning operation. Few researchers also concluded that utilisation of hybrid nanofluid can show better performance as compared to monotype of nanofluid so that, the complete machining performance can be upgraded up to noted level (Junankar et al., 2019c).

Table 5 Summary of prior research work related to utilisation of hybrid nanofluid in turning

References	*Workpiece*	*Hybrid nanofluid*	*Monotype nanofluid*	*Mode of supply*	*Output variables*	
Sharma et al. (2017a)	AISI 304 steel	Al_2O_3/MoS_2	Al_2O_3	MQL	1	Cutting force
					2	Surface roughness
Singh et al. (2017)	AISI 304 steel	Al_2O_3/GnP	Al_2O_3	MQL	1	Surface roughness
					2	Cutting force
Sharma et al. (2017b)	AISI 304 steel	Al_2O_3/GnP	Al_2O_3	MQL	1	Cutting temp.
					2	Tool wear
Jamil et al. (2019)	Ti-6Al-4V	Al_2O_3/CNT	--	MQL	1	Surface roughness
					2	Cutting force
					3	Tool life
					4	Cutting temp.
Thakur et al. (2019a)	En24 steel	Al_2O_3/CuO	--	MQL	1	Surface roughness
					2	Tool wear
					3	Cutting temp.
					4	Cutting force
Thakur et al. (2019b)	En24 steel	Al_2O_3/CuO	--	MQL	1	Surface roughness
					2	Cutting temp.
					3	Cutting force
Gugulothu and Pasam (2020)	AISI 1040 steel	MWCNT/MoS_2	--	MQL	1	Surface roughness
					2	Tool wear
					3	Cutting temp.
					4	Cutting force

The above reported various hybrid nanofluids utilised in turning operation shown noticeable results as compared to individual one. Due to synergetic effect of combination of two nanoparticle, minimisation of coefficient of friction observed along with the self-laminated-tribo-film in-between tool and work material (Dai et al., 2016). These valuable phenomenons upgraded the turning operation performance in terms of all stated response variables.

6 Conclusions

Hybrid nanofluid is the novel type of cutting fluid synthesised from two nano-shaped metal/metal oxides otherwise blending of both particles in the cutting fluid. The properties, preparation methodologies, synthesis methods, characterisation techniques and current research applications of monotype as well as hybrid nanofluid discussed in this review paper. This review study concluded that hybrid nanofluids are the most significant one as compared to monotype of nanofluid as cooling environment during turning operation. The utilisation of hybrid nanofluid in turning operation resulted into one of the important sustainable development. The major outcomes from prior research work are:

- The combination of hybrid nanofluid and MQL cooling environment provides better results as compared to other conventional cooling environments.
- Amongst all the thermo-physical properties of hybrid nanofluid, thermal conductivity observed as one the most vital and evaluated property which defines the thermal characteristics of nanofluid.
- Most of the eminent investigators preferred two step technique for the generation of hybrid nanofluid as compared to one step method. Also, XRD, SEM, TEM and EDAX are most preferred characterisation methods of hybrid nanofluid utilised by the researchers.
- The turning operation performance in terms of response variables enhanced under hybrid nanofluid and MQL cooling environment. For the performance enhancement, synergetic effect generated by the combination of two nanoparticles plays vital role.

After the current review study, main finding can be noted that hybrid nanofluid is the capable cutting fluid for turning operation. But, very few experimental research works is reported related to utilisation of hybrid nanofluid for turning operation. The appropriate extensive and planned research studies have to be performed to explore the sustainable development and to enhance the performance of turning operation. With the extensive research in this domain, leads to make the hybrid nanofluid as an economical viable and sustainable cutting fluid in future.

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