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ADVANCED EXPERIMENTAL INVESTIGATIONS ON NANOFLUIDS AS QUENCHANTS IN METAL ALLOY HEAT TREATMENTS

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ABSTRACT:

Recently, nanofluids have played an essential role in their use as a cooling medium in various disciplines in both scientific and industrial sectors. There are different fields of study of nanofluids, which have been intensely investigated theoretically, experimentally, and numerically. Metallurgical applications have allowed the implementation of nanofluids as a cooling medium in different applications. This compilation analyzed research on nanofluids as a cooling medium in heat treatments of metals, mainly steel. Factors that affect the heat extraction process in heat treatments and the effect on the microstructure and mechanical properties, such as type of nanoparticles, concentration, base fluids, particle size, temperature, shape, and surfactants, are discussed. Many variables add complexity to the heat extraction process in heat treatment processes. For this reason, research on the use of nanofluids in the heat treatment of steel is minimal, and there are discrepancies in the results obtained by researchers, which implies an enormous potential for further studies on the subject.

Keywords: Nanofluids, quenching, heat treatment, heat transfer.

RESUMEN:

Recientemente, los nanofluidos han desempeñado un papel esencial en su uso como medio refrigerante en diversas disciplinas, tanto en el sector científico como en el industrial. Existen diferentes campos de estudio de los nanofluidos, que han sido intensamente investigados teórica, experimental y numéricamente. Las aplicaciones metalúrgicas han permitido la implementación de los nanofluidos como medio refrigerante en diferentes aplicaciones. En esta recopilación se analizan las investigaciones sobre nanofluidos como medio refrigerante en tratamientos térmicos de metales, principalmente acero. Se analizan los factores que afectan al proceso de extracción de calor en los tratamientos térmicos y el efecto sobre la microestructura y las propiedades mecánicas, como el tipo de nanopartículas, la concentración, los fluidos base, el tamaño de las partículas, la temperatura, la forma y los tensoactivos. Muchas variables añaden complejidad al proceso de extracción de calor en los procesos de tratamiento térmico. Por este motivo, la investigación sobre el uso de nanofluidos en el tratamiento térmico del acero es mínima, y existen discrepancias en los resultados obtenidos por los investigadores, lo que implica un enorme potencial para nuevos estudios sobre el tema.

Palabras clave: Nanofluidos, temple, tratamiento térmico, transferencia de calor.

1. INTRODUCTION

Since the end of the 20th century, thanks to the work of Choi [1], who introduced the concept of Nanofluid, and the study of the improvement of thermal properties of colloidal suspensions with nanoparticles as heat transfer media, it has become a topic of great interest in the field of research, due to its improved thermal properties, as well as its advantage over other suspensions with microparticles that present difficulties in terms of stability, erosion, high demand for pumping power, among others. A nanofluid is a base fluid , which could be of several natures, containing a dispersion of solid particles of nanometric size, such as ceramic oxides, metals, nitrides, and carbides, among others.

Several reports have been made by researchers on the characteristics and properties of nanofluids (NF), focusing on fabrication methodologies and evaluation of stability [2–5], heat and mass transfer mechanisms [6–11], as well as the rheological properties [12–17]. In the heat treatment field, it is common to face problems that affect the microstructure and mechanical properties of metallic materials, so nanofluids can be an efficient alternative to avoid these complications.

Currently, there are many types of research on NF's fabrication with different base fluids; some of these base fluids are used in the heat treatment of steel, and studies have been carried out on the addition of nanoparticles in these media, such as water [18–26], mineral/synthetic oils [27–29] and polymeric solutions [30–37]; however, their behavior and application in this field have not been extensively studied. Therefore, it is necessary to carry out experimental research to elucidate the phenomena during cooling using NF in heat treatment applications, as well as the estimation of heat transfer coefficients and the optimal parameters for their use, since it has been found that NF provides greater control over the microstructural morphology that is subjected to heat treatment. This review pretend to summarize the published papers on evaluating the cooling characteristics and its effect on mechanical properties of alloys quenched with different nanofluids in the heat treatment of metallic materials.

2. NANOFLUIDS AS METAL ALLOYS QUENCHANTS

Heat treatments of metals consist of heating-cooling cycles intending to produce structural changes in the crystal lattice, which define the final properties of the material. In this sense, the alloying elements play an essential role in determining the final properties of the steel, however, at a high cost. On the other hand, the cooling stage in the thermal cycle is another of the most critical processes for conferring the desired material properties. This process strongly depends on the thermophysical properties of the cooling medium, such as density, viscosity, specific heat, and thermal conductivity, among others, which will define how the heat extraction mechanisms will be performed in the cooling process.

Research groups have shown that nanofluids have features to face these common problems of cooling media in heat treatment since addition of these nanomaterials modify the thermophysical properties and heat extraction mechanisms. Nanofluids make it possible to control the cooling rate of a base fluid by modifying different factors such as the chemical composition of the nanoparticles, their morphology and their concentration.

2.1. Cooling performance of nanofluids in quenching

Thanks to the research carried out by Shiro Nukiyama [38], it is known that the cooling of heated probes in a liquid medium involves different heat extraction mechanisms depending on the temperature difference between the hot surface of the parts and the cooling medium employed, so that cooling is divided into the vapor layer stage, nucleate boiling stage and convective stage. In this sense, the heat treatment industry is limited to using conventional cooling media such as water, saline solutions, and oils, which produce frequent problems during cooling. However, volatile media present vapor layer formation for long periods, and the boiling process affects the homogeneity during cooling. At the same time, higher viscosity media such as oils have a lower heat extraction capacity, providing poor mechanical properties in the treated parts. In the phase transformation processes of metals, the cooling rate control plays an essential role since heat treatments provide the final mechanical properties. Quenching is one of the most frequently employed and is performed in different media, such as water, polymeric solutions, salt baths, and oils of various types, among others.

Research in nanofluids has demonstrated their great potential in different cooling applications since heat extraction from these fluids is increased in most cases. In this regard, Quadros et al. [39] analyzed the effect of using different nanofluids as cooling media and agitation on the heat transfer of nanofluids using a Tensi stirring system. The cooling mediums used are distilled water and aqueous fullerene nanofluids with concentrations of 0.02, 0.2 y 0.4 %vol., and TiO_2 nanofluids with 0.0002, 0.002 y 0.02 %vol. The agitation velocity was 0, 500, 1000, and 1500 rpm. The nanofluid rewetting properties were measured and compared with those of distilled water. The nanofluids showed a higher transition temperature and less time to transition from the vapor phase to nucleated boiling than distilled water. The maximum heat flux was 3.26 MW/m^2 , and the fastest heat extraction was 0.2 %vol. fullerene nanofluid. Nanofluids containing 0.02 %vol. fullerene had the lowest heat flux value of 2.55 MW/m^2 . The maximum heat fluxes of the other nanofluids were in the intermediate range.

Ismail et al. [40] studied the heat transfer of 50×15 mm cylindrical copper specimens during cooling in water-based nanofluids and compared it with the results of cooling with distilled water. Nanofluids were prepared with nanoparticle types such as Al_2O_3, SiO_2, and TiO_2 with a volume fraction of 0.001 %. The probe was subjected to quenching from an initial temperature of 600 °C in nanofluids to saturation temperature (100 °C), and the process was repeated six times. The results showed that the cooling in nanofluids behaved randomly during the first cooling, indicating a deterioration in heat transfer with SiO_2 nanofluid and an improvement in Al_2O_3 and TiO_2 nanofluids compared to distilled water. However, all nanofluids after successive cooling showed an improvement in cooling time.

Cooling in TiO_2 nanofluid showing the most significant improvement compared to distilled water. They concluded that surface oxidation causes heat transfer deterioration; conversely, a mixed effect of oxidation and nanoparticle deposition during the cooling process alters the surface roughness of the specimen and improves wettability. Therefore, the impact of the vapor layer on the surface during boiling may influence the bubble dynamics in the nucleated boiling stage so that the rapid cooling of the specimen is enhanced.
Rahimian et al. [41] experimentally obtained the cooling and boiling curves of cylindrical stainless-steel probes instrumented with a thermocouple at the center of the piece using water at saturation temperature and two different nanofluids (SiO_2 and TiO_2) with 0.1 %wt. as cooling medium. The objective is to investigate the effects of surface nanoparticle deposition on the boiling heat transfer since it has been shown that nanoparticles fill the cavities, modifying the macroscopic properties of the surface, such as roughness and wettability (contact angle). Using the experimental system shown in Figure 1 a), they obtained the boiling curves by measuring the temperature at the center of the probe, solving a one-dimensional transient inverse heat conduction model. Their results show a reduction of the cooling time by 50 %, which is attributed to the accumulated deposition of nanoparticles on the cylinder surface at each subsequent cooling, while the critical heat flux has a similar increase in both NF of up to 120 %. The heat transfer rate at the boiling stage increased with repetitive cooling in SiO_2 nanofluid, as observed in Figure 1 b).

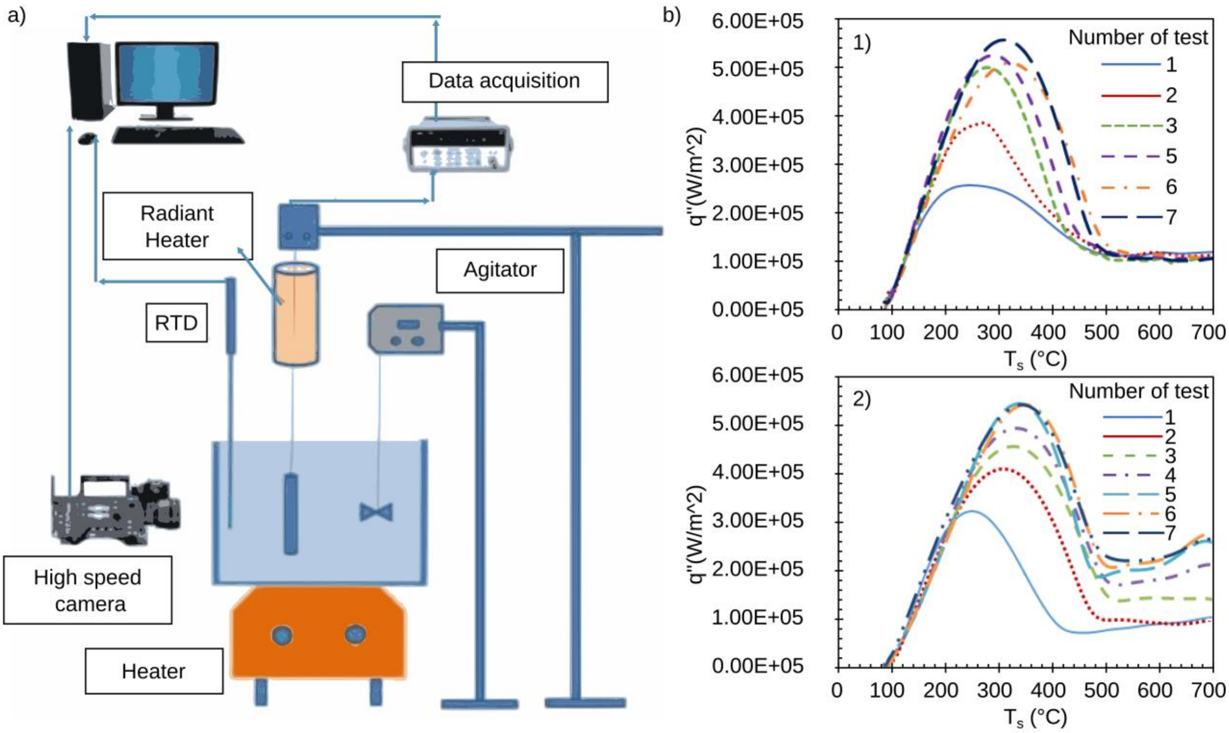

Figure 1: a) Schematic diagram of the experimental system; b) Boiling curves for repetitive tests, 1) TiO_2 nanofluid y 2) SiO_2 nanofluid at saturated conditions [41].

George et al. [42] determined the performance of Al_2O_3 nanofluid and water-based Al_2O_3-TiO_2 hybrid nanofluid as a quenching medium in quenching tests of Ti3l2.5 V plates with dimensions of 130×60×6 mm. Their results revealed that both NF improved the cooling efficiency of titanium plate, as shown in Figure 2. The Al_2O_3-TiO_2/water hybrid nanofluid shows a significantly higher value of cooling rate by about 15 % compared to conventional cooling fluids. In addition, the hybrid nanofluid exhibits marginally higher efficiency than the Al_2O_3/water nanofluid.

Nayak et al. [43] studied different cooling media and evaluated their heat transfer characteristics. They used distilled water, aqueous graphene, and multi-walled carbon nanotube (MWCNT) nanofluids at concentrations of 0.01-0.3 and 0.0003-0.3 %vol., respectively, as cooling media. They used instrumented Inconel specimens according to ISO 9950 standards to obtain the thermal history during cooling. The experiments were conducted in a standard Tensi stirring system at 0, 500, 1000, and 1500 rpm velocities. The heat flux was obtained using the inverse heat conduction method. The results of the heat transfer analysis showed a maximum average heat flux of 3.23 MW/m^2 and faster heat removal with 0.1 %vol graphene nanofluid.

Tiara et al. [44] studied the heat transfer rate of an AISI 304 steel plate in the transition and nucleated boiling regimes using the jet impingement methodology employed in the cooling systems used in the exit table of a hot rolling mill. For the experiment, they used a 100×100×6 mm plate. The plate was heated to an initial temperature of about 900 °C.

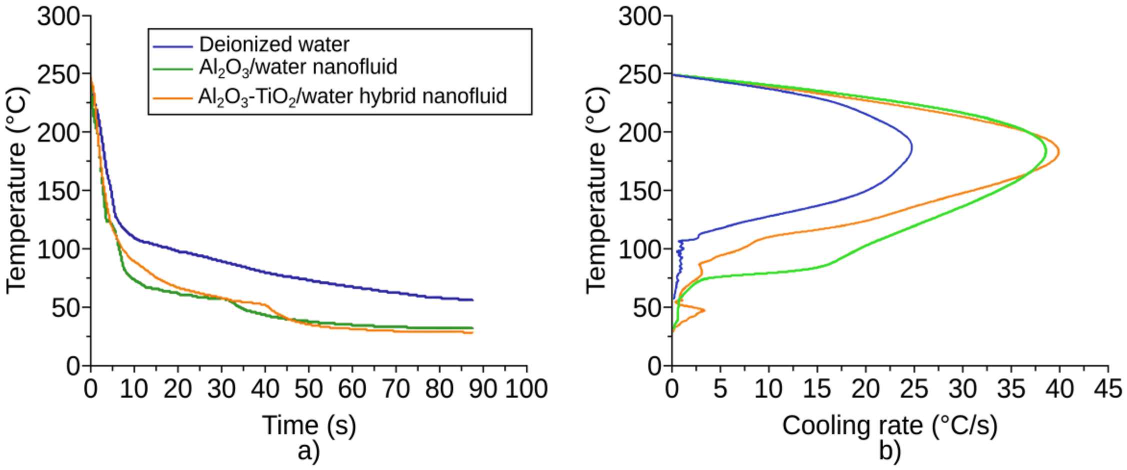

Figure 2: a) Cooling curves for both NF and deionized water; b) Cooling rate curves for both NF and deionized water [42].

The nanofluid employed is layered double hydroxide Cu-Al (LDH) at 120 ppm with different additives at optimized concentrations of sodium dodecyl sulfate (SDS), cetyltrimethylammonium bromide (CTAB), polyoxyethylene sorbitan monolaurate (Tween 20) and polyvinylpyrrolidone (PVP). They observed that the maximum cooling rate was achieved in the case of Cu-Al LDH/Tween 20 nanofluid due to improved thermal conductivity and reduced surface tension; the nanofluid with SDS showed the minimum values of thermal conductivity and surface tension; the PVP-based nanofluid showed a better cooling rate than that of the CTAB surfactant due to a higher increase in thermal conductivity.

Additionally, in [45] they performed the synthesis and characterization of Zn-Al layered double hydroxide (LDH) nanofluid for use as a potential coolant in the steel industry, using an experimental system consisting of spray nozzle cooling of an instrumented 304L stainless steel plate. They analyzed the effect of particle concentration in the range of 40 to 240 ppm on the enhancement of thermal conductivity and viscosity and compared it with water quenching. An optimum cooling rate of 125 °C/s was obtained for a nanofluid concentration of 160 ppm, 1.29 times higher than that of water and presents the highest CHF with a value of 2.29 MW/m^2 . The last is correlated to that nanofluid concentration showed a maximum increase in thermal conductivity of about 11 % and the lowest viscosity value of 0.786 MPa among the six concentrations. Compared to water, the heat transfer rate from the surface and, hence, the surface heat flux is higher for nanofluids. The last can be attributed to the decrease in the thickness of the vapor film on the surface during the cooling process since the heat transfer rate is higher for thinner vapor films due to the reduction in the rewetting time required to re-establish direct contact with the hot surface.

Similarly, Chakraborty et al. [46] conducted experiments with Cu-Al (LDH) nanofluids at 120 ppm, used as a coolant in spray nozzles on 100×100×6 mm plates. Their study evaluates the effect of varying the Cu: Al ratio on thermal conductivity, stability, and heat transfer in steel cooling. They performed Cu:Al molar ratio optimization experiments by varying the ratio Cu: Al=2:1, 4:1, and 6:1 at a fixed nanofluid concentration of 120 ppm. The results show that all combinations achieved the highest cooling rate and heat flux at a molar ratio 4:1. Once the optimized molar ratio was selected, they conducted cooling experiments by varying the nanoparticle concentration over 40-240 ppm. A maximum cooling rate of 168.6 °C/sec was achieved with a concentration of 160 ppm, which is 26 % higher than that of water. A maximum thermal conductivity improvement of 15.17 % was also observed.

Patra et al. [47] investigated the cooling characteristics of water and a water-based nanofluid with 0.001 %vol. Al_2O_3 nanoparticles using an experimental system consisting of a vertical 316L stainless steel rod of 12×1000 mm with an internal heater. They performed tests with an initial temperature of 200-250 °C by varying experimental cooling conditions and constant water and nanofluid flow rates. The cooling curves follow a general trend of rapid temperature decrease to almost 100 °C at the probe surface, regardless of the operating parameters and thermocouple location. The results obtained during the cooling process indicated that the nanofluid's HTC (heat transfer coefficient) is higher than that of deionized water, as shown in both cases in Figure 3. It was observed that, under the same conditions, the cooling time of the sample with the nanofluid decreased considerably compared to that obtained using water. It is also shown that nanofluids can improve the heat transfer performance in terms of cooling rate for a long vertical bar by causing liquid droplet-induced nanoparticle deposits, resulting in a pre-coating effect characterized by enhanced wettability.

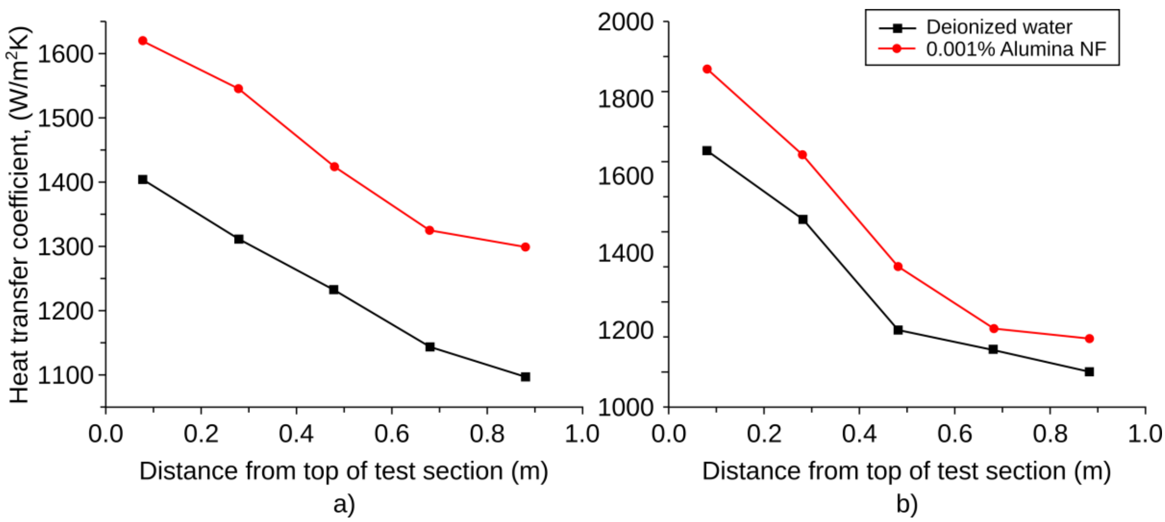

Figure 3: Variation of the heat transfer coefficient with axial position for an initial specimen temperature of 250 °C and a flow rate of 7 g/s. a) Non-continuous heating case b) Continuous heating case with DH of 14,557 kW/m2 [47].

Chinchole el al. [48],performed quenching experiments on zircalloy tubes in water and water based Al_2O_3 nanofluids. Their results show that the nanofluids exhibit a reduction in quenching time, as observed in Figure 4. This reduction is likely caused by forming a thin film by the deposition of particles on the sample surface, improving the wettability conditions by optimizing heat transfer.

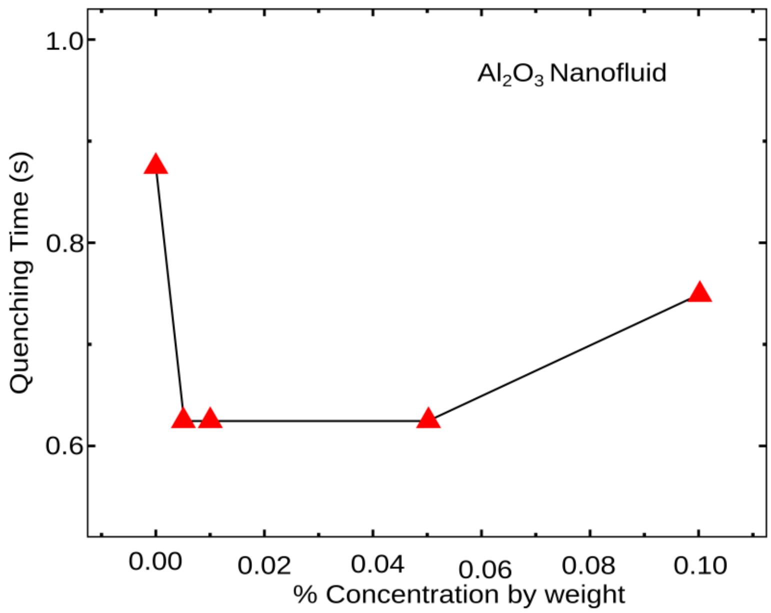

Figure 4: Quenching time for nanofluids of Al_2O_3 [48].

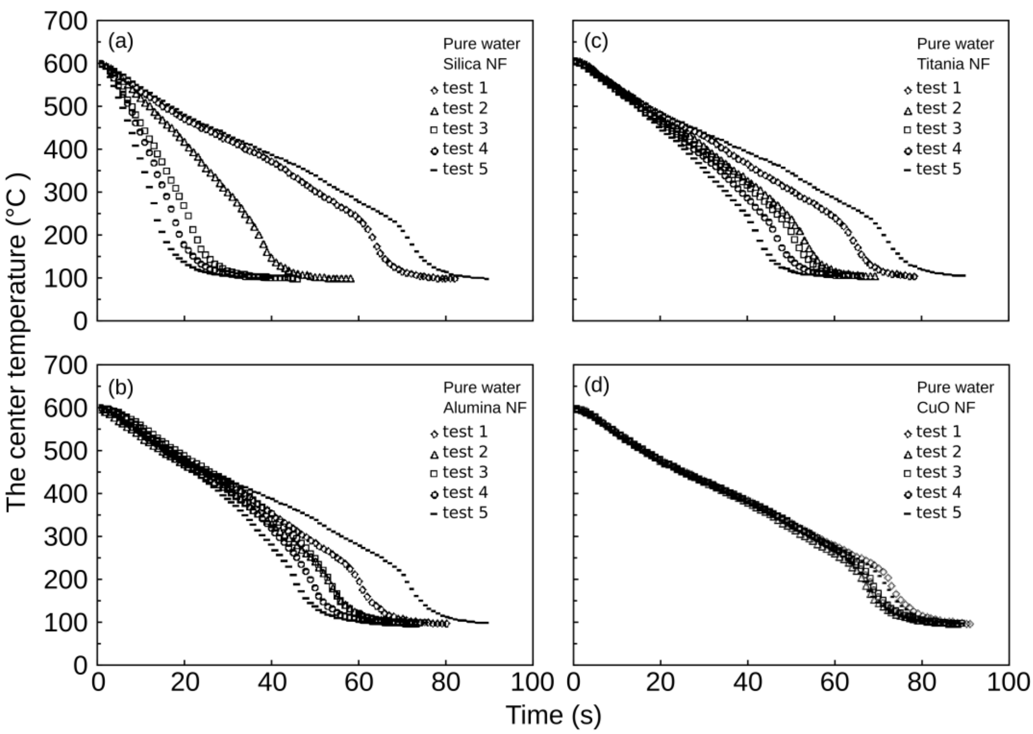

Figure 5: Time-temperature curves of nanofluids (0.1 %vol.) at saturated conditions [49].

Ciloglu et al. [49], experimentally studied the heat extraction of various water-based nanofluids by addition of SiO_2, Al_2O_3, TiO_2 y CuO a 0.1 %vol., using a brass sphere as a test specimen. Experimental results showed that the quenching performance of the test specimen depended on the type of nanofluids. SiO_2 nanoparticles improved the heat transfer performance in the boiling stage and proved the best coolant for cooling than the other nanofluids. Figure 5 shows the thermal histories of the different nanofluids.

Khoshmehr et al. [50] studied the cooling and boiling curves during the cooling of silver cylindrical specimens instrumented with thermocouples and surface roughness of 129 and 690 nm. They used two fluids as cooling media: deionized water and multi-walled carbon nanotube (MWCNT) water-based nanofluid with four different concentrations. For the calculation of heat transfer, they employed the Lumped capacity method. Their results indicated that the CHF in the nanofluids was lower than that of deionized water. They also observed that under identical circumstances, by repeating the test, the cooling time of the sample in both water and nanofluid decreased. Comparison between surface roughness revealed a significant effect, such that the specimen with higher surface roughness cooled in less time.

Zupan et al. [51] investigated the cooling characteristics in base fluids such as water and polyalkylene glycol PAG with the addition of Al_2O_3 and TiO_2 nanoparticles with different particle sizes ranging from 50 nm to 100 µm at concentrations of 0.1-0.4 %wt. Their results show a shorter cooling process, although the maximum cooling rate is similar for all media. At lower concentrations of TiO_2 nanoparticles dispersed in water, there is no significant difference between the cooling curves for deionized water and TiO_2 nanofluid. Alumina particles suspended in a water-based polymer solution shorten the vapor film phase and initialize the nucleating boiling phase earlier than the polymer solution without oxide particles. At higher particle content, fluids with smaller particles exhibit better cooling properties than those with larger particles and the base fluid without particles due to increased specific surface area, leading to better heat transfer conditions.

Babu et al. [52] studied the effect of carbon nanotube (CNT) concentration and agitation on the heat transfer rate during immersion cooling in CNT nanofluids. For this purpose, nanofluids were prepared by suspending chemically treated CNTs (TCNTs) at four different concentrations in deionized water (DI) without surfactant. They used instrumented 304L stainless steel probes of dimensions 20×50 mm for water quenching and CNT nanofluids at concentrations of 0.25 and 1.0 %wt.

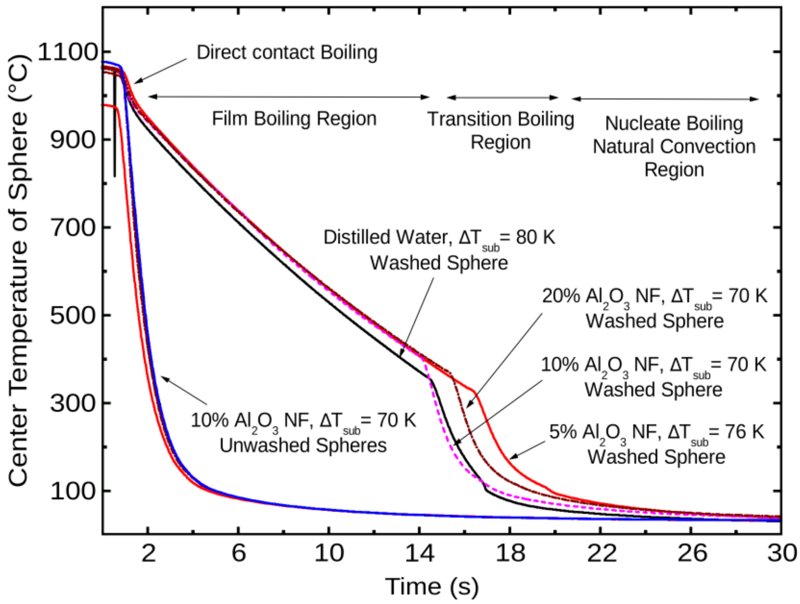

Figure 6: Cooling curves at the center of a 10 mm diameter sphere in water and nanofluids Al_2O_3 with subcooling of 70∼80 K [53].

They calculated heat flux and temperature at the cooled surface using inverse heat conduction. Their results revealed that the critical heat flux (CHF) increased with increasing CNT concentration up to 0.50 %wt. this is attributed to its higher effective thermal conductivity. On the other hand, they noted that CHF decreased with increasing CNT concentration due to the increase in viscosity.

The effect of agitation during cooling was counterintuitive and resulted in a reduction of the heat transfer rate with increasing agitation speed.

Park et al. [53] experimentally investigated the characteristics of boiling phenomena in the quenching of stainless-steel spheres in Al_2O_3 nanofluids and compared them with water tests. The differences in boiling film heat transfer rates between water and nanofluids increase when the subcooling of the liquid decreases, according to Figure 6. The heat fluxes tend to decrease when the concentration increases. They observed that during repeated cooling of the specimens with the nanofluids, without the removal of particles deposited on the surface, there is no vapor layer formation, so they suggest that this deposition of nanoparticles on the surface of the sphere prevents the formation of a vapor layer, which consequently promotes the rapid cooling of the sphere.

2.2 Mechanical properties obtained with quenching nanofluids

In the metallurgical industry, materials with more specific characteristics are being produced, so it is necessary to research for developing technology to carry out the phase transformation process, since conventional routes do not meet the requirements of the new needs of materials in high-performance applications. Heat treatment processes has limitations, which often cause losses in the final properties of the material. Frequent problems include undesired hardness profiles, distortion, and cracking. There are several studies focused on evaluating the effect of the use of nanofluids as a cooling medium on the microstructure and mechanical properties in the heat treatment of different types of steel alloys, there is a wide range of possibilities that can be explored to provide the appropriate conditions according to the chemical composition of the alloys to be treated as well as the desired mechanical properties.

Zaharudin et al. [54] prepared TiO_2 nanofluids based on cooking oils such as palm, sunflower, canola, and corn, both new and waste. They evaluated the stability of each nanofluid by observation, thermal conductivity, and zeta potential methods. The nanofluids were used as quenchants in a heat treatment to a high carbon steel. The probes were heated to 950 °C, cooled in the different quenching media, and then analyzed their microstructure and hardness. They concluded that adding nanoparticles in the base fluid increases the thermal conductivity and improves the heat transfer of the base fluid. The cooling process with oil-based nanofluid produced a martensitic structure; sunflower waste oil and corn oil with TiO_2 are unstable after 30 days of observation; palm oil and canola oil with TiO_2 provide the highest hardness and thermal conductivity.

Salas et al. [55] studied the effect of quenching with γ-Al_2O_3 nanofluid on the microstructure and hardness of an AISI-SAE 1045 steel. The NF employed mineral quenching oil as the base fluid and 0.5 %wt. of γ-Al_2O_3 nanoparticles. They were fabricated by the two-step method, applying 30, 60, and 120 minute ultrasound times and SPAN80 surfactant amounts of 0.5 and 1 %wt at 60 °C. The results show that by using NF, hardness similar to those obtained with quenching in the base fluid are not achieved; however, for high and low Span80 contents at longer ultrasound times, the dispersion measurement of HV hardness measurements shows higher hardness and a more homogeneous microstructure, in addition, they report an increase in the thermal diffusivity of the NF as shown in Table 1.

Table 1: Dispersion of HV hardness and thermal diffusivity measurements of nanofluid [55].

# Nanofluid	Ultrasonication time (min)	Surfactant Span80 (% wt)	Standard deviation of hardness (HV)	α x 10^4 ($cm^2 \cdot s^{-1}$)
1	30	0.5	38.8	7.4
2	30	1.0	31.89	9.06
3	60	0.5	54.1	6.15
4	60	1.0	52.4	7.92
5	120	0.5	18.21	7.66
6	120	1.0	17.65	10
Base fluid				1.94

Prabu et al. [56] studied the effect of TiO_2 /synthetic oil nanofluids in heat treatment of hardenable alloy steel EN24 and high carbon steel with a minimum chromium content of 12 %, SS420. They varied the concentration of TiO_2 nanoparticles by 0.25, 0.375, 0.5 and 0.625 gr/lt. The probes were austenitized at 850 °C (EN24) and 980 °C (SS420) and cooled in the nanofluids. The results showed an improvement in the hardness and a reduction in the cooling time. In addition, comparative analysis indicates that the samples quenched with the nanofluid's heat transfer characteristics and properties were improved. They revealed that increasing the cooling rate increases the number of treatments in a specific period, which will help increase the production throughput. On the other hand, the material properties are varied after the cooling process with different samples of NF. They observed that the increase in hardness was about 5-10 % using NF as a coolant in both materials. Figure 7 shows the thermal histories and hardness profiles for the materials studied.

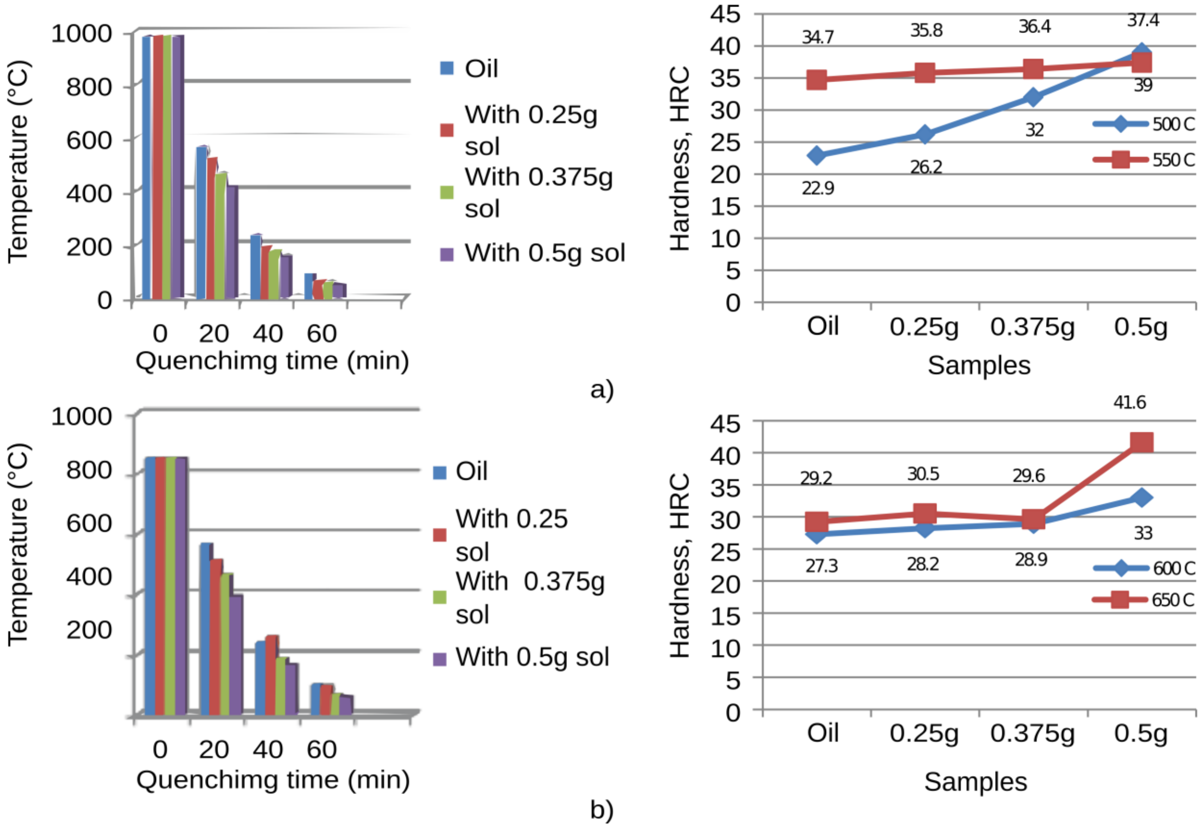

Figure 7: Hardness profiles; a) EN24 steel, b) SS420 steel [56].

Mahiswara et al. [57] quenched cylindrical AISI 1045 steel probes of dimensions 15×10×10 mm. The steel probes were austenitized at 1000 °C for 60 min. They used an oil-based nanofluid with laboratory-grade carbon powder nanoparticles in concentrations of 0.1, 0.2, 0.3, 0.3, 0.4, and 0.5 %vol. as quenchant. The results in Figure 8 a) show that oil-based nanofluid produces a martensitic structure. However, above 0.2 %vol. the microstructure consists mainly of a pearlitic phase. The maximum hardness is observed at 0.2 %vol. with 570.98 HV. Higher particle concentration produced lower hardness values, attributed to particle agglomeration.
Overall, the hardness value remains higher than quenching without nanoparticle addition. They concluded that nanoparticles within the fluid can enhance the cooling to obtain the desired hardness with an appropriate concentration of nanoparticles.

In the same way, Kresnodrianto et al. [58] performed the same experiments but using water as the base fluid. The microstructural and hardness study shows that the volume fraction of the nanoparticles used in the nanofluids significantly affected the cooling process. After cooling with water-based nanofluids, the microstructure was observed to consist mainly of martensite. Figure 8 b) shows that the maximum hardness is kept at 0.2 %, 885.34 HV. The hardness decreases with 0.3 %, increases again with 0.4 %, and decreases with 0.5 %. This anomaly was attributed to the poor mixing process by ultrasonic vibration, which caused accumulation between the carbon nanoparticles. The hardness value is higher than that caused by cooling with the fluid without added nanoparticles. They conclude that nanoparticles in the fluid can improve the hardness of the fluid with proper concentration.

Likewise, Oktavio et al. [59] performed experiments on the same material with a water-based nanofluid at the lower and upper carbon nanoparticle concentrations, 0.1 and 0.5 %, respectively. They added different concentrations of surfactant Dodecylbenzenesulfonic acid (SDBS) 0, 1, 3 and 5 %. The results of the hardness tests correspond to the hardness of the quenching media, with a maximum hardness of 845HV for 0.1 % carbon with 1 % SDBS and 878HV for 0.5 % carbon with 3 % SDBS. The hardness tests show a significant improvement over the results without adding SDBS. In addition, they observed that as the surfactant addition increases, a lower hardness occurs due to particle accumulation, as shown in Figure 8 c).

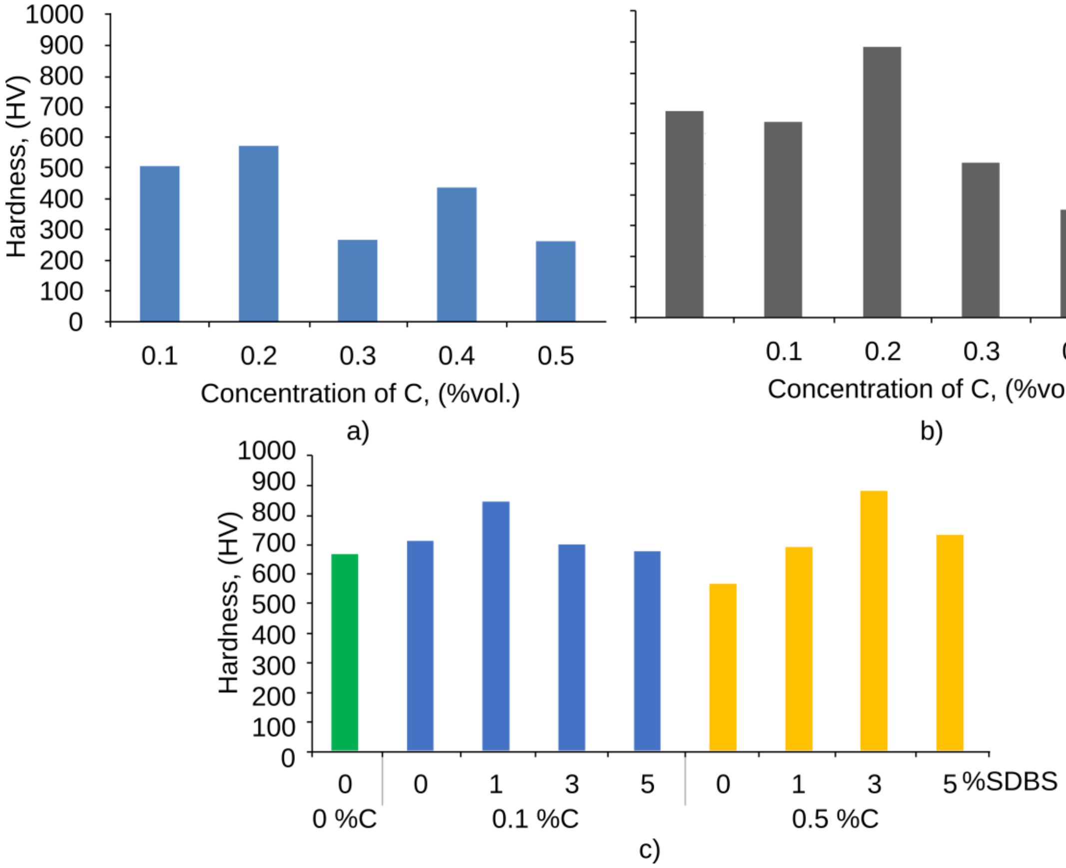

Figure 8: S45C steel hardness profiles a) Oil-based nanofluid [57] b) Water-based nanofluid [58] c) Water-based nanofluid with SDBS surfactant [59].

Babu et al. [60] performed quenching experiments on AISI 1010 steel cylindrical specimens with dimensions of 20×50 mm using carbon nanotube (CNT)-based nanofluids. They analyzed the effect of CNT dispersion and concentration on the microstructure and mechanical properties. For the dispersion of CNTs, they performed two procedures: the first one consisted of adding Triton X100 surfactant until dispersion was achieved, and the second one was a chemical treatment of the particle surface in an acidic mixture of HNO_3 and H_2SO_4 in a volumetric ratio of 1:3 for five h to produce TCNTs. The nanofluids were fabricated by the two-step method: 1 lt of distilled water with a TCNT concentration of 0.5 %wt.; 1 lt of distilled water with a CNT concentration of 0.5 %wt. with surfactant and a treatment in distilled water. The specimens were heated to a temperature of 850 °C for 15 min and then quenched in the three cooling media mentioned above. Their results conclude that the surface roughness of the specimens quenched in CNT nanofluids is higher (0.52 %) than that quenched in water (0.1 %) due to the deposition of nanoparticles on the specimen surface. The hardness of low carbon steel is higher in the specimens quenched in CNT nanofluids prepared without any surfactant with a value of 269 HV due to the addition of surfactant obstructing the heat transfer. Table 2 summarizes the results of their experiments.

Table 2: Surface roughness (Ra) and hardness measurements of hardened probes cooled in different quenchants [60].

Quenchant	Water	Water + CNTs	Water + CNTs + Surfactant
Surface roughness (µm)	0.1 %	0.52 %	0.1 %
Hardness (HV)	170.9	269	183.5

Table 3 is a summary of relevant findings regarding several nanofluids as quenchants in heat treatment applications and their heat transfer behavior, including qualitative and quantitative data. Information on the composition of the nanofluids used in the experiments is found, where variables such as the base fluid, type and concentration of nanoparticles are highlighted. Reports of the most relevant findings of the effect of the mentioned variables on the heat transfer characteristics and thermophysical properties of nanofluids, mechanical properties of various metallic materials, and surface effects of the test material on heat transfer during quenching, among others, are described.

Table 3: Summary of relevant findings of nanofluids as a cooling medium in heat treatment applications.

Author	Base fluid	Nanoparticle	Concentration	Findings
Sharif [37]	PAG 46	Al_2O_3	0.05-1.0 %vol.	Thermal conductivity improvement as increasing NPs
Redhwan [36]	PAG	Al_2O_3; SiO_2	0.2-1.5 %vol.	Nanofluids are stable for more than one month
Redhwan [34]	PAG	Al_2O_3; SiO_2	0.2 %vol.	90 and 120 min are the optimum sonication times
Sanukrishna [35]	PAG-based/ Synthetic oil	SiO_2	0.07-0.6 %vol.	Thermal conductivity and viscosity increased with increasing NP concentration, while they decreased with increasing temperature
Quadros [39]	Aqueous fullerene	TiO_2	0.0002-0.02 %vol.	Higher transition temperature and less time to transition from the vapor phase to nucleated boiling than distilled water
Ismail [40]	Water	Al_2O_3, SiO_2 and TiO_2	0.001 %vol.	Surface oxidation deteriorate heat transfer; a mixed effect of oxidation and nanoparticle deposition alters the surface roughness of the specimen and improves wettability
Rahimian [41]	Water	SiO_2; TiO_2	0.1 %wt.	50 % reduced cooling time; 120 % increased critical heat flux
Zaharudin [54]	Cooking oils	TiO_2	0.1 %wt.	Palm and canola oil with TiO_2 provide the highest hardness and thermal conductivity
George [42]	Deionized water	Al_2O_3; Al_2O_3/TiO_2	0.02 %w/v.	Hybrid nanofluid shows 15 % higher cooling rate
Nayak [43]	Distilled water	Multi-walled carbon nanotubes (MWCNT)	0.01-0.3 and 0.0003-0.3 %vol.	0.1 %vol. nanofluid showed the maximum heat flux and faster heat removal
Salas [55]	Mineral oil	γ-Al_2O_3	0.5 %wt./ Span80	Usage of Span80 shows higher hardness and a more homogeneous microstructure
Prabu [56]	Synthetic oil	TiO_2	0.25-0.625 gr/lt.	5-10 % hardness improvement; reduction in the cooling time
Mahiswara [57]	SAE 5W-40	Carbon nanoparticles	0.1-0.5 %vol.	Nanofluids provides higher hardness than base fluid
Kresnodrianto [58]	Water	Carbon nanoparticles	0.1-0.5 %vol.	Nanofluids provides higher hardness than base fluid, but with an anomaly behavior
Oktavio [59]	Water	Carbon nanoparticles/ SDBS	0.1 and 0.5 %vol.	The hardness show a significant improvement over the results without adding SDBS
Tiara [44]	Water	Layered double hydroxide Cu-Al (LDH) with SDS; CTAB; Tween 20; PVP	120 ppm	The nanofluid with Tween 20 provide the maximum cooling rate; SDS showed the minimum thermal conductivity and surface tension; PVP showed a better cooling rate than that of the CTAB due to a higher increase in thermal conductivity
Tiara [45]	Water	Zn-Al layered double hydroxide (LDH)	40-240 ppm	Decrease of the thickness of the vapor film with nanofluids, cause higher surface heat flux
Chakraborty [46]	Water	Cu-Al (LDH)	40-240 ppm	Maximum cooling rate with 160 ppm, which is 26 % higher than that of water; 15.17 % thermal conductivity improvement
Patra [47]	Water	Al_2O_3	0.001 %vol.	Nanofluid's HTC is higher than that of deionized water
Babu [60]	Distilled water	Carbon nanotube (CNT)	0.5 %wt.	Higher hardness of low carbon steel provided by nanofluid prepared without any surfactant
Chinchole [48]	Distilled water	Al_2O_3	0-0.1 %wt.	Nanofluids exhibit a reduction in quenching time, caused by forming a surface thin film
Ciloglu [49]	Pure water	SiO_2; Al_2O_3; TiO_2; CuO	0.1 %vol.	SiO_2 improved the heat transfer in the boiling stage
Khoshmehr [50]	Deionized water	MWCNT	0.1 %vol.	CHF in the nanofluids was lower than that of DI water; higher surface roughness decrease cooling time
Zupan et al. [51]	PAG	Al_2O_3; TiO_2	0.1-0.4 %wt.	Al_2O_3 shorten the vapor film phase and initialize the nucleating boiling phase earlier than base fluid
Babu [52]	Deionized water	CNTs	0.25 and 1.0 %wt.	CHF increased with increasing CNT concentration up to 0.50 %wt.

3. CONCLUSIONS

This article is a review of research work on the use of nanofluids as a cooling medium in heat treatment applications of metallic materials. The researchers report several results on the characteristics of nanofluids in heat transfer, including higher control and efficiency of heat transfer, improved cooling rate, optimization of cooling, reduced defects in the treated material and more homogeneous microstructure.

From this review of the state of the art it is possible to highlight factors that several investigations have in common and suggest a strong contribution to the effectiveness of heat transfer in quenching by immersion cooling. These factors are the deposition of nanoparticles on the surface and the surface quality of the test material. These factors significantly influence the heat transfer mechanisms since modifying the solid-liquid interface has a major impact on heat transfer.

Although there is a wide available information on the behavior of nanofluids in different aspects and applications, there is a need for further research on how nanofluids affect the heat transfer stages during immersion cooling, as the benefits of nanofluids in heat treatment are attributed to them. The areas of opportunity in nanofluid research applied to the heat treatment of metallic alloys are extensive due to the unique properties offered by these fluids. The main topics of research and development include the study of heat transfer mechanisms depending on the composition of the nanofluid, cooling of complex and large parts, influence of agitation, obtaining cooling curves, influence on the microstructure as well as its economic and environmental impact. Strengthening these fields of research allows for the implementation of nanofluids as a cooling medium in large-scale heat treatment.

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