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A study on damage evolution in Cu-TiO\textsubscript{2} composite fabricated at different temperatures and strain rates

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Abstract

Copper/Titanium Dioxide (CuTiO\textsubscript{2}) samples were fabricated at three temperatures (450 °C, 650 °C, 850 °C) using: a universal testing machine (quasi-statically at the strain rate of $8 \times 10^{-3}$ s\textsuperscript{-1}), a drop Hammer (dynamically at the strain rate of about $8 \times 10^{2}$ s\textsuperscript{-1}), and a modified Split Hopkinson Pressure Bar (strain rate of about $1.6 \times 10^{3}$ s\textsuperscript{-1}). The effects of reinforcing particle size on relative density and damage parameter of Cu reinforced by 0, 2.5, 5 and 10\% volume fractions of nano- and micro-sized TiO\textsubscript{2} were investigated. The results indicated that the size of TiO\textsubscript{2} particles, loading rate, and temperature had significant effect on relative density and damage parameter. The results also showed that the Quasi-Static method was superior to the other two methods. In addition, by increasing temperature, the mechanical properties of the composites were improved. The results showed that the effect of nano sized reinforcement particles on damage parameter was more profound than micro sized reinforcement particles. In this work, a new damage model considering the effects of strain rate, temperature, volume fraction and the aspect ratio of particles on damage parameter was proposed. The damage parameter was obtained using relative density and elasticity modulus. The results showed significant difference between the two methods. However, the density method yields more accurate and realistic results.

1. Introduction

The electrical and thermal conductivity of copper has made it a popular material for different applications such as the resistance welding electrode and heat exchangers. In addition, Titanium Dioxide (TiO\textsubscript{2}) due to its low cost, perfect hardness, low density and high melting temperature has gained many applications in material processing \cite{1}. In recent decades, Metal Matrix Composites (MMCs) have increasingly been used to improve the properties of metal matrix (e.g. aluminum, magnesium, and copper) reinforced by micro or nano particles (e.g. SiC, B\textsubscript{4}C, TiO\textsubscript{2}, TiB\textsubscript{2}). However, the Van der Waals force causes clustering of nanoparticles which in turn gives rise to non-uniform distribution and agglomeration of particles in metal matrix \cite{2, 3}.

Powder metallurgy (PM) is a well-known technique which is used for fabrication of MMCs. In this technique, the size, morphology and volume fraction of the matrix and reinforcement can accurately be controlled. The type of loading (Quasi-static \cite{4} or dynamic loading \cite{5}) and temperature level are important and effective parameters in PM technique. In this method, high local temperatures, which are required for the formation of metallurgical bonds between particles, are produced and consequently, the need for hot sintering is eliminated.

The effects of particles such as TiB\textsubscript{2} \cite{6, 7}, B\textsubscript{4}C \cite{8–10}, ZrO\textsubscript{2} \cite{11–13}, TiO\textsubscript{2} \cite{14–18} and their volume fractions on copper have been the subject of many investigations over the past recent years. Kato et al.\cite{19} showed that the appropriate size of copper as the matrix materials was 45 μm for TiB\textsubscript{2}. In addition, Guo et al.\cite{7} investigated the effect of the size of TiB\textsubscript{2} particles (10, 30, 70 and 110 μm) on Cu-TiB\textsubscript{2} composites and showed that by increasing the size of particles, the density and porosity decreased and increased, respectively.

Yener et al.\cite{9} studied some properties of Cu-B\textsubscript{4}C produced by cold press. They used copper and B\textsubscript{4}C with 40 μm particles size and sintered the specimens at 900 °C for two hours. Their results indicated that by
increasing the volume of the reinforcement particles (from 0 to 3%), the relative density decreased around 5% whereas the Brinell hardness increased about 12%. Fathy et al [11] produced Cu-ZrO2 nanocomposite by thermo chemical process followed by powder metallurgy technique and showed that the compressive strength increased from 312.6 MPa for pure copper to 413.5 MPa for Cu-9wt-% ZrO2.

Among the reinforcing particles, TiO2, due to its excellent mechanical and tribological properties is an appropriate reinforcement for strengthening the copper matrix composites [17]. In fact, copper reinforced by TiO2 exhibited good electrical and thermal conductivity and strength at high temperatures. Ning et al [20] showed that when the reinforcing particles are dispersed uniformly in the copper matrix, the wear properties of Cu–TiO2 composite increases considerably.

Sorkhe et al [15] studied the mechanical properties and electrical conductivity of Cu–TiO2 (TiO2 particles size was about 10–30 nm) using SEM, x-ray diffraction, and TEM. They showed that adding nano particles increased yield strength, ultimate tensile strength, Young’s modulus, hardness, and decreased elongation and relative density. By comparing the results, the copper based composite reinforced by about 2.5 wt-% TiO2 was suggested for resistance welding electrodes.

The damage and fracture of ductile materials is a challenging subject which has been broadly studied in recent decades. From micromechanical and mesoscale point of view, the damage in ductile materials is caused by void nucleation, growth, and coalescence. On the other hand, damage accumulation of MMCs is due to fracture of reinforcement particles, matrix voiding, and particle/matrix deboning [21]. Kouzel et al [21] showed that for the increased reinforcing particles size or volume fraction, the fracture of particles is the main reason of damage evolution while for the decreased size of reinforcing particles size or volume fraction, matrix voiding is the dominant mechanism of damage in MMCs [22]. Matrix voiding often occurs between closely located reinforcement particles. The results of tensile tests on AA7075–SiC and AA2124–SiC were discussed by Doel et al [23] and Srivatsan et al [24], respectively. Rutecka et al [25] showed that the reinforcement particles reduced the strength of material because, in some cases, particles in clusters could be insufficiently bonded to the matrix.

Two well-known available methods for the study of damage field are micro–mechanical theories (Goursoun-Tvergaard–Needleman (GTN) [26, 27] and Rousselier [28, 29]) and continuum damage mechanics ((CDM) Lemaitre [30] and Voyiadis [31]). There are quite a number of methods for measuring the damage based on different hypotheses: Young’s modulus, Density, Ultrasonic waves and Electrical resistance [32].

The growth and coalescence of voids which is the cause of damage evolution in specimen decreases the density of the specimen [33, 34]. Moussy [35] studied the ductile damage of the steel based on density reduction using Archimedes principle [36] for different strain hardenings. Three specimens including notched and plain tensile and rolled specimens were investigated in this investigation. The highest density and consequently the highest damage were observed for the notched tensile specimens, plain and rolled specimens, respectively. The same results was also observed by Maugin [37].

Lemaitre [30] suggested a simple damage potential with only one material constant to describe a damage growth law. The constant was calculated from tensile test by assuming the constant value for stress triaxiality. Furthermore, Lemaitre [30] found the dependency of the constant on four parameters: equivalent plastic strain at the damage initiation, damage at the threshold, equivalent plastic strain at fracture, and the critical damage. Lemaitre suggested a linear relation between damage and plastic strain, although the relation is nonlinear in reality. Thakkar and Pandey [38] modified Lemaitre model for considering the nonlinear behavior of material by adding two parameters to the model.

The study of damage parameter in Cu–TiO2 specimens (with nano and micro reinforcement particles and prepared by PM method) based on density is the main purpose of this paper. The specimens are prepared at the three different temperatures of 450 °C, 650 °C, and 850 °C and three different loading rates using (a) a Split Hopkinson Bar (SHP), (b) a Drop Hammer (DH), and (c) the universal tensile testing machine, Santam. In addition, the effects of reinforcing particle size on relative density and damage parameter of samples are also studied in this work. Finally, a new equation based on the experimental measurements is presented for the damage parameter in terms of strain rate, temperature, volume fraction and the aspect ratio of particles.

2. Materials and methods

The main objective of this work is to study the damage evolution in Cu–TiO2 composite. The composite is fabricated from copper powder with purity of 99.99% and reinforced by titanium dioxide nanoparticles (TiO2 np with the average size of 20 nm and spherical morphology) and titanium dioxide microparticles (TiO2 mp with the average size of 1.5 μm and spherical morphology). The appropriate size of the copper particles as the matrix was 45 μm [19]. The copper powder with particle size of 45 μm and purity of 99.9% was purchased from Merck Company, Germany. The SEM images of the copper and TiO2 powder are shown in figure 1. The figure illustrates that the Cu particles have dendritic morphology with particle size of around 45 μm.
Volume fractions of 0, 2.5, 5, and 10% of nanoparticles and microparticles were used for fabrication of the composite specimens. Mechanical milling with 10mm steel balls and ball-to-powder mass ratio of 10:1 was used to prepare the MMC specimens. Figure 2 shows the SEM images of a copper particle after mixing and milling with TiO2 nano reinforcement particles at two different magnifications (Cu-5%TiO2). These images clearly show the uniform distribution of reinforcement particles on copper particles. After milling, the specimens were produced by hot pressing technique. Dynamic compaction was accomplished by SHB and DH and quasi-static compaction was performed using Santam. More details of the mechanisms of SHB, DH and Q-S powder compaction processes can be found in [39]. The flow chart of the procedure of nano/micro composite fabrication and test program is presented in figure 3. Furthermore, specimens are specified by the compaction type followed by TiO2 volume fractions (0, 2.5, 5, and 10%) and size (Micro or Nano) in MMCs. For example, QS-2.5%M and DH-5%N denote the specimens fabricated by Quasi-Static method with 2.5% volume fraction of microparticles and Drop Hammer method with 5%volume fraction of nanoparticles, respectively.

3. Results and discussion

3.1. Density measurement
By considering the rule of mixture [40], the theoretical density was calculated as follows:

\[ \rho_{th} = (\nu \times \rho_{TiO2}) + [(1 - \nu) \times \rho_{Cu}] \]  

(1)

where \( \rho_{th} \) is the theoretical density of the nanocomposite and microcomposite samples, \( \rho_{TiO2} \) is the density of TiO2, \( \rho_{Cu} \) is the density of copper, and \( \nu \) is the volume fraction of nano/micro particles. The densities for TiO2 and Cu are 4230 and 8960 kg m\(^{-3}\), respectively. Theoretical densities of Cu-TiO2 nanocomposite and microcomposites reinforced by 0, 2.5, 5 and 10% volume fractions of nanoparticles and microparticles are given in table 1.
Relative density ($\rho_{Rc}$) is defined as the ratio of measured density ($\rho_{\text{exp}}$) to theoretical density as follows:

$$\rho_{Rc} = \frac{\rho_{\text{exp}}}{\rho_{\text{th}}}$$  \hspace{1cm} (2)

Archimedes principle was employed to measure the experimental density [36]. Figures 4 and 5 show variation of relative density for the three compaction methods (Santam, drop hammer, and Split Hopkinson bar) for different volume fractions of TiO$_2$ particles (0%, 2.5%, 5%, and 10%) at (a) 450 °C, (b) 650 °C and (c) 850 °C for nano and micro particles, respectively. A similar trend can be observed in all figures (nano and micro particles), i.e. the relative density decreases with the increasing TiO$_2$ volume fraction (due to clustering of particles) [36] and strain rate. The reason for the latter is that for very high strain rates or high-velocity compactions, the entrapped air between particles cannot escape and as a result the porosity of the composite increases at high loading rates. The pores prevent full densification of the powder [41–43] and consequently the density of the composite decreases. This allows for the formation of packets of air that prevent perfect bonding between the particles during the compression process and reduces the final density of the fabricated samples. Moreover, the relative density increases with the increase in temperature. In fact, at higher temperatures, the powder’s hardness and yield strength decrease and as a result the compressibility of the powder increases [44].
Figure 4. Relative density for the three compaction methods for different volume fraction of TiO$_2$ nanoparticle at (a) 450 °C, (b) 650 °C, and (c) 850 °C.
Figure 5. Relative density versus the three compaction methods for different volume fraction of TiO$_2$ microparticle at (a) 450 °C, (b) 650 °C, and (c) 850 °C.
The compatibility between the matrix and the reinforcing particles in composites is reduced by hard particles in a soft and deformable matrix. This is due to the fact that the effect of loading rate on the relative density is more profound for TiO$_2$ nanoparticles than that for the TiO$_2$ microparticles.

Figure 6 shows variation of relative density versus the particle size (nano and micro) for the specimens fabricated under Q-S loading and at 850 °C. According to the figure, the relative density of nanocomposite is higher than that of the microcomposite. However, the effect of particle size on relative density is more significant for higher values of TiO$_2$ volume fractions. For example, for Cu-10 vol.10% TiO$_2$ specimen, the relative density of the microcomposites is about 2.6% lower than that for the nanocomposites. However, the relative density generally decreases by adding reinforcement to copper. So, the relative density of Cu-TiO$_2$ microcomposite and nanocomposites decreases by 6.5% and 3.8%, respectively, while the volume fraction of reinforcement particles increases from 0% to 10%.

3.2. Microstructure analysis
The Energy Dispersive Photoelectron Spectroscopy (EDS) was used to study the composition of the particles contained in the sample. Figures 7(a) and (b) show a point that was selected to obtain EDS and EDS spectrum of QS-5%N at 650 °C, respectively. As the figure shows, the specimen contains Cu (K), titanium (LA) and oxygen.
(KA) only and no more impurity was recognized. Additionally, the elemental mapping was performed to confirm the formation of Cu-TiO$_2$ nanocomposite and the uniform distribution of TiO$_2$ in the Cu matrix that can be seen in figures 8 to 10 at 650 °C for the three compaction methods Q-S, DH and SHB.

The microstructure of the MMCs was investigated through SEM analysis. Figure 11 shows the SEM images of the produced Cu-5%TiO$_2$ for the three different compaction methods at 650 °C. As the figure shows, the
number of pores and defects, indicated by red circles, and crack, indicated by yellow color, in the samples are increased by increasing the strain rate.

Figure 12 shows the effect of temperature on the QS-5%N specimens. As the figure suggests, by increasing the temperature the quality of comaction was improved and the pores and defects specified by red circles were decreased.

Figure 9. Elemental mapping of the specimen DH-5%N at 650 °C showing the uniform distribution of oxygen and titanium in Cu matrix.
The SEM images of CuTiO$_2$ are shown in figure 13 for 650°C for the three compaction methods (a) Q-S, (b) DH and (c) SHB. As the figure indicates, the least damage occurs for the QS compaction method.

3.3. Damage parameter based on density

Various methods can be found in literature to calculate the damage parameter [32] in materials. In one of the methods, damage parameter ($D$) is described in terms of density as follows [32]:

\[
D = \frac{\rho - \rho_0}{\rho_0}
\]

where $\rho$ is the current density and $\rho_0$ is the initial density.
Figure 11. SEM micrographs for Cu-5\%TiO$_2$ nanocomposite at 650 °C for the three compaction methods (a) Q-S, (b) DH and (c) SHB.

Figure 12. SEM micrographs for QS-5\%N at different temperatures (a) 450 °C, (b) 630 °C and (c) 850 °C.

Figure 13. SEM micrographs for Cu-5\%TiO$_2$ microcomposite at 650 °C for the three compaction methods (a) Q-S, (b) DH and (c) SHB.

$$D = 1 - \left( \frac{\rho}{\rho_{\text{in}}} \right)^3$$
where \( \tilde{\rho} \) and \( \rho_{\text{un}} \) are density of damaged and non-damaged states, respectively. In this study, to measure the damage parameter, the theoretical and experimental densities are considered as damaged and non-damaged states of samples, respectively.

Variations of damage parameter versus dimensionless temperature \( (T / T_{\text{Rm}}) \) where \( T_{\text{Rm}} \) is the room temperature in Kelvin for nanocomposite of Cu-TiO\(_2\) (0%, 2.5%, 5% and 10%) compacted using the three compaction methods as explained before are shown in figure 14. As the figure suggests, the temperature shows opposite effect on the relative density and damage parameter so that by increasing the temperature, relative density has increased and damage parameter has decreased. As the figure indicates, damage parameter, regardless of the temperature level, is lower for the Q-S loading condition than the others two methods. An inverse trend can be observed for the relative density. The results shown in figure 14 suggest that a linear and a power law trend governs the damage parameter versus the dimensionless temperature, \( T / T_{\text{Rm}} \). The relation between the damage parameter and the dimensionless temperature can be defined as follows:

\[
D = A_1 \left( \frac{T}{T_{\text{Rm}}} \right)^m + B_1
\]

where \( A_1 \) and \( B_1 \) are constant and should be identified by experiment.

Variation of damage parameter versus loading rate (compaction method) at 850 °C for nano and microcomposite specimens are shown in figures 15 and 16, respectively. As the figures show, the damage parameter for SHB is higher than that for the other two methods and the damage parameter of nanocomposite is lower than that of the microcomposite. In addition, regardless of the compaction method, the increase of reinforcement volume fraction brings about the increase in the damage parameter.

Variations of damage parameter versus logarithmic dimensionless strain rate for MMCs (nano) are shown in figure 17. In this figure, \( \dot{\varepsilon}_0 \) is the reference strain rate and is considered 0.001 in this work. As the figure indicates, the damage parameter increases by increasing the strain rate. Furthermore, for the same strain rate, by increasing temperature, the damage parameter decreases. The relation between the damage parameter and strain rate can be defined as follows:
where $A_2$ and $B_2$ are constant and must be determined by experiment.

Volume fraction of particles plays important role on damage parameter. Figure 18 shows variation of damage parameter versus the reinforcement volume fraction at 850 °C for the three compaction methods, nano and micro particles. As mentioned before, the increase of volume fraction gives rise to the increase of damage parameter. From figure 18 the variation of damage parameter versus the reinforcement volume fraction can be expressed as follows:

$$D = A_3 V_P^2 + B_3 V_P + C_3$$  \hspace{1cm} (6)

Where $V_P$ denotes the particle volume fraction. In addition, $A_3$, $B_3$ and $C_3$ are constant and must be determined by experiment. Volume fraction is defined in terms of MMCs and the reinforcing particles densities as follows [40]:

$$V_P = (\rho_{th} - \rho_{Cu}) / (\rho_{TiO_2} - \rho_{Cu})$$  \hspace{1cm} (7)

Particles aspect ratio $(S)$ is another effective parameter on damage parameter and is equal to the ratio of TiO$_2$ and Cu particle size. In this paper, the size of Cu particles, TiO$_2$ nano and micro particles are 45 μm, 20 nm, and
1.5 μm, respectively. Variation of damage parameter versus particles aspect ratio is depicted in figure 19. As the figure suggests, by increasing S, damage parameter increases. From the figure, the relation between damage parameter and particles aspect ratio can be defined as follows:

\[ D = A_4S + B_4 \]  

(8)

As it is observed, four parameters including temperature, strain rate loading, volume fraction, and particle aspect ratio, which have significant effect on damage parameter in MMC specimens fabricated via PM technology were studied in this work. In order to cast the effects of these parameters in a single relation simultaneously, equations (4) to (8) can be combined to give:

\[ D = \left( A_1 \left( \frac{T}{T_{01m}} \right)^m + B_1 \right) \left( A_2 \log \left( \frac{\varepsilon}{\varepsilon_0} \right) + B_2 \right) \left( A_3 V_p^2 + B_3 V_p + C_3 \right) \left( A_4S + B_4 \right) \]  

(9)

The constants \( A_1 \) to \( B_4 \) in equation (9) were obtained through curve fitting technique using the experimental data provided in figures 4 to 19 and the SOLVER of the Microsoft Excel software as an iterative nonlinear optimization algorithm [45]. The scatter plot of the damage parameter obtained from experiment and predicted by equation (9) is shown in figure 20. As it is observed, the root-mean-square error (RSME) of the fitting is 0.025 which is acceptable and indicates that the damage equation fits the best for all samples. In other words, it has the least scatter and the greatest density around the 1:1 line. The constants of equation (9) for Cu-TiO₂ composite are listed in table 2.

A comparison between the damage parameters predicted by the damage model (equation (9)) and obtained by the experiment is shown in figures 21 to 24. As it is seen, the comparison has been made for the four variables studied in this work including the dimensionless temperature, \( \frac{T}{T_{01m}} \), strain rate, \( \frac{\varepsilon}{\varepsilon_0} \), reinforcement volume fraction, \( V_p \) and particle aspect ratio, S. In each figure, variation of damage parameter has been plotted versus one of the above four mentioned varying parameters while the other variables have been assumed constant. As the figures suggest, there is reasonable agreement between the damage model and the experiments.
3.4. Damage parameter based on Young’s modulus degradation

Young’s modulus reduction in loading-unloading cyclic test is one of the well-known methods to calculate the damage parameter. In this method, by considering the initial and the current Young’s modulus, the damage parameter is calculated as follows:

\[ D = 1 - \frac{E}{E_0} \]  

(10)

where \( E \) and \( E_0 \) are the current and the initial Young’s modulus, respectively. In addition, the composite Young’s modulus of the non-damaged state is given as [40]:

Figure 18. The effect of TiO\(_2\) size on damage parameter for microcomposites and nanocomposites at 850°C for (a) Q-S, (b) DH and (c) SHB.
where $E_c$, $E_p$, and $E_M$ are Young’s moduli of the composite, reinforcing particles and the matrix, respectively. In this study, Young’s moduli of the copper and TiO₂ are 120 GPa and 230 GPa, respectively. The theoretical values of the composites Young’s modulus are provided in table 3 for the reinforcement volume fractions used in this work.

Attempts were also made to obtain the Young’s moduli of the composites by experiment. Since, the PM samples were too small for tensile or even compression test, indentation test was employed alternatively for measuring the Young’s moduli of the composite specimens. The details of the indentation test can be found in...
Figure 20. Scatter plot of the damage parameter obtained from experiment and predicted by equation (9).

Figure 21. Variation of damage parameter, predicted by the damage model and obtained from the experiments, versus the dimensionless temperature (strain rate = 0.008, $S = 0.0004$).

Figure 22. Variation of damage parameter, predicted by the damage model and obtained from the experiments, versus the strain rate (Temperature = 850 °C, $S = 0.0004$).
Figure 23. Variation of damage parameter, predicted by the damage model and obtained from the experiments, versus the reinforcement volume fraction (strain rate = 0.008, S = 0.0004).

Figure 24. Variation of damage parameter, predicted by the damage model and obtained from the experiments, the aspect ratio (strain rate = 0.008, temperature = 850°C).
In addition, the theoretical values of the Young's moduli were considered as an initial or non-damage state to calculate the damage. The current values of the composites' Young modulus are listed at Table 4.

Figures 25 and 26 show the variation of damage parameter calculated based on Young's modulus using equation (10) for different temperatures and compaction methods (Q-S, DH and SHB) for nanocomposite and microcomposite. The results are similar to those obtained from the density method, i.e. the damage for nanocomposite is less than that for the microcomposites and by increasing the temperature, the damage parameter decreases. In addition, the damage parameter for Q-S compaction method is less than that for the other two compaction methods.

A comparison between the damage parameter of Cu-0% TiO₂ calculated using the methods based on the density and Young's modulus for the three compaction methods is shown in figure 27 for different temperatures. As the figure indicates, the damage parameter computed based on density varies between 0.05 to 0.12 while the damage parameter calculated using the Young's modulus method ranges from 0.4 to 0.6. Since, the reasonable range of damage as reported by Bonora et al [43] and Testa et al [44] varies between 0 to 0.3, it may be concluded that density method is a more accurate method for evaluation of damage evolution in composites fabricated by PM method. The earlier results reported by Bonora et al [43] suggested that the damage parameter varied between 0.8 to 1. However, Bonora et al [43] noticed that the effects of specimen's geometry changes, due to changes in gage length and reference sectional area, on the specimen stiffness in plastic deformation had not correctly been taken into account and that the range of damage must be corrected. They showed that the damage parameter is less than 0.3.

In fact, in Young's modulus method, plastic strain is the most effective parameter on damage evolution as stated by Bonora [47]. On the other hand, in PM method plastic strain is very high. Therefore, it is reasonable to conclude that damage is overpredicted by Young's modulus method. Lemaître and Lippmann [32] believed that the damage measured based on Young's modulus reduction is appropriate only when damage is uniformly distributed in the volume for which the strain is measured.

### 4. Conclusion

The following conclusions may be derived in this study:

1. For the same temperature, strain rate and volume fraction of reinforcing particles, the relative density of nano composite was higher than that of micro composite.

2. The Q-S compaction method was superior to DH and SHB compaction methods. In fact, the properties of composites reduced with strain rate.

3. The damage parameter of MMCs depended on four parameters: temperature, strain rate, volume fraction, and particles aspect ratio. The damage increased by increasing strain rate, volume fraction and particle aspect ratio and decreased with temperature.

4. The damage was defined by an empirical equation incorporating the effects of the four forgoing parameters in the equation.

5. Damage was obtained based on density and Young modulus measurements. It was shown that the density method could yield more accurate and realistic results.

| Material       | Temperature | 450°C | 650°C | 850°C |
|----------------|-------------|-------|-------|-------|
| Cu-0%TiO₂      | Q-S         | 55    | 49    | 42    |
|                | DH          | 61    | 56    | 50    |
|                | SHB         | 68    | 63    | 59    |
| Cu-2.5%TiO₂-Nano| Q-S         | 62    | 66    | 59    |
|                | DH          | 70    | 68    | 63    |
|                | SHB         | 77    | 76    | 72    |
| Cu-5%TiO₂-Nano | Q-S         | 70    | 58    | 51    |
|                | DH          | 75    | 63    | 59    |
|                | SHB         | 81    | 73    | 69    |
| Cu-10%TiO₂-Nano| Q-S         | 60    | 35    | 48    |
|                | DH          | 68    | 60    | 58    |
|                | SHB         | 72    | 68    | 63    |
| Cu-2.5%TiO₂-Micro| Q-S        | 59    | 62    | 56    |
|                 | DH          | 68    | 65    | 60    |
|                 | SHB         | 74    | 73    | 69    |
| Cu-5%TiO₂-Micro| Q-S         | 67    | 54    | 49    |
|                | DH          | 71    | 61    | 57    |
|                | SHB         | 78    | 70    | 66    |
| Cu-10%TiO₂-Micro| Q-S        | 56    | 52    | 46    |
|                 | DH          | 66    | 58    | 55    |
|                 | SHB         | 70    | 65    | 60    |
Figure 25. Damage parameter calculated based on Young’s modules degradation (equation (10)) versus the three compaction methods for different volume fraction of TiO$_2$ nanoparticles at (a) 450 °C, (b) 650 °C, and (c) 850 °C.
Figure 26. Variation of damage parameter based on Young’s modules degradation (equation (10)) versus three the compaction methods for different volume fractions of TiO$_2$ microparticle at (a) 450 °C, (b) 650 °C and (c) 850 °C.
Figure 27. A comparison between the damage parameters of Cu-0% TiO$_2$ calculated using the methods based on the density and Young's modulus for different temperatures (a) Q-S, (b) DH and (c) SHB.
Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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