Numerical validation of thermal conductivity of Al6061 based hybrid nano metal matrix composite filled with nanoparticles of Ni and Cr

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Abstract
Aluminum composite matrix materials are regarded as the most popular type of composite materials. Metal matrix composites made of aluminum have better mechanical and thermal properties, including a higher strength-to-weight ratio, tensile strength, hardness, and a low coefficient of thermal expansion. In various types of applications viz, automobile, aviation, the thermal characterization of aluminum metal matrix composites has increased. Thermal conductivity as a function of temperature, thermal diffusivity, and the thermal gradient is one of the essential thermal characteristics of aluminum metal matrix composites needed to understand the material’s behavior. The current work evaluated thermal conductivity as a product of thermal diffusivity, density, and specific heat for Al6061/Ni/Cr hybrid nano metal matrix composites from 50 °C to 300 °C. Al6061 based metal matrix composite reinforced with varying wt.% of Ni and Cr nanoparticles whereas fixed wt.% of graphene and Mg added to improve thermal conductivity, self-lubrication, and wettability. Thermal diffusivity, specific heat, and density were evaluated using laser flash apparatus (LFA 447), differential scanning calorimetry (DSC), and Archimedes principle, respectively. Results revealed that the thermal conductivity of fabricated composites increases with Ni, Cr, Mg, and graphene nanoparticles. With further expansion of reinforced particles of Ni and Cr, the thermal conductivity decreases. Finite element analysis (FEA) has been conducted to determine the thermal gradient and thermal flux using experimental values such as density, thermal conductivity, specific heat, and enthalpy at various temperature ranges to validate the experimental results.

1. Introduction
Aluminum is a commonly used material in several industries, including automation, construction, packaging, aviation, and, of course, product design (Shuvho et al 2020). They use two or more micron or nanoscale filler materials to create hybrid metal matrix composites with superior properties over monolithic metal and single filler reinforced metal matrix composites (Ramesh et al 2009). As a result, in the twenty-first century, composite materials are in high demand to solve all traditional materials’ problems (Gui and Kang 2000).

Composites are mostly two-phase materials, with one phase (matrix) continuous and the other discontinuous (reinforcement). Matrix keeps reinforced particles together, forms the necessary shape, transfers the load to and between mounts, protects struts from the environment, and enhances material properties. The reinforcement carries the gear that is added to the composite. The matrix properties are improved by the reinforcements’ exceptional mechanical and thermal properties (Chandlla et al 2017).

As opposed to the characteristics of a matrix material alone, composite materials typically reveal superior aspects (Miracle and Donaldson 2002, Smith, 2004). Hybrid metal matrix composites (HMMCs) are pioneering materials with infinite potential for modern materials research and production. These materials have a higher temperature, yield strength, and modulus of elasticity, as well as the ability to be improved by various thermal and
showed that composite reinforced with coarse particles of SiC has a high thermal conductivity. The degree of reliability they affect the mechanical behavior of the composites at high temperatures. HMMCs components have a high thermal parameters of composites like thermal diffusivity and specific heat helps calculate thermal conductivity. Finite element analysis (FEA) was used to perform a computational analysis of metal matrix composites (MMGs).

Thermal studies of aluminum metal matrix composites (AMMCs) are becoming increasingly relevant in various applications. This aids in comprehending the properties of metals or alloys that change with temperature. The thermal expansion and thermal conductivity of HMMCs have been rigorously studied because they affect the mechanical behavior of the composites at high temperatures. HMMCs components have a high degree of reliability (Sharma et al 2016). Molina and Rheme (2008) investigated the thermal characteristics of an aluminum-based metal matrix composite reinforced with varying SiC particle volume percent. SiC particles of sizes 170 μm and 16 μm were used to create the composite. When the size of the SiC reinforced particle was increased from 16 μm to 170 μm; the authors noticed an improvement in thermal conductivity. The results showed that composite reinforced with coarse particles of SiC has a high thermal conductivity.

Chu et al (2009) utilized the powder injection molding and pressure infiltration process to synthesize large volume fractions (56–65 vol. percent) of SiCp/Al composites with various reinforcements particle size distributions. An analogous diameter method for the thermal conductivity of composites with a multimodal size distribution has been projected for data analysis and modeling. In addition, the results obtained using the proposed method were compared to experimental evidence and found good agreement between both. Chaudhary et al (2021a) in their research paper Optimization of WEDM process parameters for machining of heat-treated ASSAB 88 tool steel using Response surface methodology (RSM), has clearly stated that the effect of the servo reference voltage (SRV), peak current (PC), wire feed speed (WFR), and wire tension (WT) on material removal rate (MRR) and surface roughness (SR) of tool steel material and found that the optimal solution is at a set of 117 sample points. Chaudhary et al (2021b) in his research paper WEDM machining of heat treated ASSAB 88 tool steel: A comprehensive experimental analysis. Investigated different materials to produce intricate geometries of components and finally suggested that ASSAB steel is the ultimate material when enriched with annealing and quenching it shows that the quenched sample showed increased hardness whereas the annealed one shows the decrement in hardness and the increase in properties is shown for the heat treated elements rather than the untreated one.

Son et al (2011) investigated the thermal activity of MMGs reinforced with SiC particles. The coefficient of thermal expansion has been compared to 2D FEM modeling and analytical models such as the Kerner and Turner models under 1, 10, and 20 thermal cycles, with temperature limits up to 200 °C. The coefficient of thermal expansion increased during thermal cycling, with the solid agreement between the Kerner model and the 2D FE model after 20 cycles.

Okumus et al (2013) researched on the thermal properties of an Al6061-Si/ SiC/graphite hybrid metal matrix composite reinforced with different sizes (45 μm and 53 μm) and weight percent (5, 7.5, and 10) of reinforced particles. On a laser flash apparatus, a thermal conductivity test was performed. The authors discovered that manufactured composites with a higher content of graphite particles had better dimensional stability. The findings showed that the thermal conductivity decreases by increasing the weight percentage and decreasing the size of SiC and graphite particles. Jeong et al (2014) investigated the thermal properties of a graphene-reinforced Al-based metal matrix composite. Friction stir processing was used to make this composite (FSP). The authors discovered that graphene/Al MMGs have higher thermal conductivity than the base metal matrix, Al alloy, but due to the addition of graphene to Al alloying matrix tensile strength and indentation resistance is decreased drastically.

Wagh (2016) examined the thermal activity of Al/Al2O3/Mg nanocomposite with Mg reinforced particles. According to the author, thermal conductivity, which is dependent on free electrons, increased with increasing temperature. Dislocation density and porosity affect moving electrons. Since Mg has a higher thermal conductivity than Al2O3, the thermal conductivity coefficient is increased as the weight percentage of Mg is enhanced to matrix material. Krishna et al (2016) investigated the computational simulation of thermal characteristics of Al6061 dependent MMC reinforced with varying wt.% of SiC and fixed vol.% of graphite particles. Computational models were developed, and the magnitude of thermal conductivity was compared to analytical models such as ROM, Series model, Geometric model, and Maxwell model. The importance of thermal conductivity was found to be marginally lower than the experimental value. Thermal diffusivity and thermal conductivity decreased as the volume fraction of reinforced particles SiC and Gr increased cumulatively.

It is apparent from the previous research that the investigation of AMMCs has received more attention and applause. If these materials are to be used in a wide range of engineering applications, the thermal properties of AMMCs must be prioritized. As a result, it is essential to evaluate the thermal properties of hybrid composites while transforming from design to production process. However, only a tiny amount of research has been done on the thermal analysis and material analysis of Al6061/Ni/Cr hybrid nano metal matrix composites.
The importance of computational thermal analysis of hybrid composites has been emphasized, as work on FEA analysis of composites has been minimal.

2. Fabrication and sample preparation

Hybrid nano metal matrix composites have been fabricated through the stir casting route as per table 1. Five samples were prepared according to procedures followed in ASTM standardization. Machine requirements for thermal diffusivity and specific heat tests to determine the thermal conductivity of composites. As per ASTM specifications, test specimens are prepared in the form of a cylindrical shape with a diameter and thickness of 12.7 mm and 3 mm respectively were prepared to observe thermal diffusivity. The sample size for estimating specific heat capacity is approximately 10 mg of powder or granules. The samples have been fabricated to the required dimensions. With different sample sizes, five specimens were considered separately to determine thermal diffusivity and specific heat. The stir casting process which is considered as the predominant process of manufacturing the metal matrix composites is prepared according to ASTM D695 by this standardization we achieve the desired composites for ultimate mechanical and microstructural characterization.

3. Thermal conductivity characterization of HNMMCs

The NETZSCH model LFA 447 was used to test thermal diffusivity from 50 °C to 300 °C. Four samples were made with different wt.% nano reinforcement (Ni, Cr, Mg, and Gr) and Al6061 as the matrix. A temperature range of 50 °C to 300 °C, was chosen to cover the entire functional range of the composite maintaining a resistance action of liquid phase formation in the microstructure of matrix material (Krishna et al 2015).

Assessment of thermal conductivity, the specific heat of formed HNMMCs must be determined. Differential scanning calorimetry was used to quantify specific heat in samples containing 10 mg of formed composites. Thermal conductivity was calculated using thermal diffusivity, specific heat, and density of formed HNMMCs. The experimental density of developed HNMMCs is calculated by the Archimedes principle, whereas the rule of mixture method calculates theoretical density. Porosity is observed due to variation in theoretical and experimental density.

Because of the increase in contact surface area with air, porosity increased as the wt.% of graphene and Mg as reinforced nanoparticles in the matrix rose. As a result, both were applied at a fixed 0.6 and 0.5 percent. (Reddy et al 2019, Irhayyim et al 2020). Table 2 shows that as the weight percentage of reinforced nanoparticles increases, the porosity increases.

The decrease of thermal conductivities at elevated temperatures diminishes the thermal diffusivity with the addition of reinforcements. Thermal conductivity was observed to decrease as the blending temperature of Ni and Cr nanoparticles is increased. In the high-temperature field, the temperature confidence of thermal conductivity is dominated by the decrease in thermal diffusivity. At temperatures below room temperature, the

(HNMMCs). The importance of computational thermal analysis of hybrid composites has been emphasized, as work on FEA analysis of composites has been minimal.

| Table 1. Planning for fabrication of HNMMCs. |
|-----------------------------------------------|
| Samples of HNMMCs | Al6061 | Nickel (Ni) | Chromium (Cr) | Graphite (Gr) | Magnesium (Mg) |
|-------------------|--------|-------------|---------------|--------------|----------------|
|                   | gm     | %           | gm            | %            | gm             | %            |
| HNMMC1            | 488.5  | 97.7        | 3             | 0.6          | 3              | 0.6          | 2.5           | 0.5           |
| HNMMC2            | 485.5  | 97.1        | 3             | 0.6          | 6              | 1.2          | 3             | 0.6          | 2.5           | 0.5           |
| HNMMC3            | 485.5  | 97.1        | 6             | 1.2          | 3              | 0.6          | 3             | 0.6          | 2.5           | 0.5           |
| HNMMC4            | 482.5  | 96.3        | 6             | 1.2          | 6              | 1.2          | 3             | 0.6          | 2.5           | 0.5           |

| Table 2. Density and porosity of Al6061 and HNMMCs. |
|-----------------------------------------------|
| Sample no. | Composition designation | Fundamental density (g cm$^{-3}$) | Measured density (g cm$^{-3}$) | Porosity (%) |
|------------|------------------------|----------------------------------|-------------------------------|--------------|
| Al6061     | Al6061                 | 2.7                              | 2.697                         | 0.12         |
| HNMMC1     | Al6061/0.6Ninp/0.6Crnp | 2.723                            | 2.669                         | 1.98         |
| HNMMC2     | Al6061/0.6Ninp/1.2Crnp | 2.731                            | 2.637                         | 3.44         |
| HNMMC3     | Al6061/1.2Ninp/0.6Crnp | 2.733                            | 2.612                         | 4.43         |
| HNMMC4     | Al6061/1.2Ninp/1.2Crnp | 2.741                            | 2.603                         | 5.03         |
specific heat decreases rapidly and increases the dependency of thermal conductivity on temperature (Okumus et al. 2012).

It can be observed that the thermal diffusivity of hybrid composites decreases for varying weight fractions at all temperatures. It has been depicted that there is a linear decrement of thermal diffusivity over the range of temperatures (table 3).

Table 4 shows the specific heat of hybrid nano metal matrix composites increases with the addition of reinforced particles up to 0.6 wt.%, further addition lowers the specific heat observed. As the temperature rises from 50 °C to 300 °C, the specific heat of formed HNMMCs and Al6061 gradually increases.

Thermal conductivity decreases as the thermal diffusivity and density of hybrid composites decrease. In the high-temperature area, it has been observed that the minimization of thermal diffusivity makes a lot of dependency level of temperature upon thermal conductivity. As the content of Ni and Cr is increased, the thermal conductivity decreases. Table 5 shows as the temperature increases, there is a gradual increase in thermal conductivity. HNMMC1 has a higher thermal conductivity of 203.2 W mK⁻¹ than other developed HNMMCs and Al 6061 at 300 °C, while Al 6061 has a low thermal conductivity of 168.2 W mK⁻¹. It has been observed that by adding graphene to Al6061, the thermal conductivity increases, further graphene is kept constant for other developed HNMMCs. This confirms the addition of graphene in a minimal amount has a significant influence. In contrast, Ni and Cr nanoparticles have an insignificant effect on the rise in thermal conductivity of advanced hybrid nano metal matrix composites. Al6061/Ni/Cr exhibits better thermal conductivity with minimum reinforced nanoparticles and graphene, providing better thermal stability.
4. FEA simulation for thermal behavior of the HNMMCs

Due to the linkage between reinforced particles and matrix, the controlled manner of Ni, Cr, Mg, and graphite in the Al6061 matrix is not only defined over a large regime in the current situation, but it also cannot display representative behavior due to the stipulated regulated regimes over all feasible metal matrix composites fabrication. FEM analysis was performed in this case for Ni, Cr, Mg, and graphite in an Al6061 matrix, which can achieve thermal activity.

The aim of the finite element analysis is to build a three-dimensional solid model of nanoparticle reinforced HNMMCs. As a consequence, FEA is a valuable method for measuring the thermal properties of newly formed HNMMCs. The computational investigations of thermal gradient and thermal flux are carried out to correlate the thermal conductivity of HMMCs using the experimental values of HNMMCs, namely thermal conductivity, specific heat, and enthalpy.

For evaluating the thermal effects of composite materials, thermal flux and thermal displacement are useful. Thermal flux is an important parameter for predicting the formed composites' thermal characteristics, such as thermal conductivity. The heat flow rate per unit area determines thermal flux. The thermal gradient is the ratio of temperature variation to displacement variation. The use of thermal gradient analysis to determine the thermal behavior of composites may be useful. Table 6 displays the disc shape model, fine mesh generation, and contour plots of thermal flux and thermal displacement computed using ANSYS R18.1 for various percentage compositions of HNMMCs. In this finite element analysis of disc shape model for thermal behavior, 1.7 mm element used during meshing is hexahedron solid. Densities, thermal conductivities, specific heat capacities, and enthalpies of various HNMMCs are some of the major boundary conditions taken into account. Heat transitions from the higher temperature end (red) to the lower temperature end (blue) can be seen in the contour plots.

Computational values for thermal flux and thermal displacement of composites under analysis between 50 °C and 300 °C are shown in tables 7 and 8 respectively.

At 300 °C, the maximum and minimum thermal flux obtained for HNMMC1 and Al6061 are 42729 W m⁻² and 40508 W m⁻², respectively. When comparing FEA and theoretical results, there was very little difference in thermal flux.

At 50 °C–300 °C, HNMMC1 has a higher thermal flux than Al6061 and HNMMCs. Thermal flux is directly proportional to the thermal conductivity of the composites, so HNMMC1 has a higher thermal conductivity value between 50 °C and 300 °C.

If the temperature rises, the thermal gradient increases, but as the weight percent of reinforcement increases, it decreases. At 300 °C, Al6061 (54078 °C m⁻¹) has a lower thermal gradient than HNMMC1 (54831 °C m⁻¹), which has a higher thermal gradient. The experimental results of the thermal gradient are found to be in substantial agreement with the theoretical results.

Even more good mesh refinement has been achieved, the accuracy of the results has been retained, and there has been no significant variance in the results. Mesh independence or convergence tests have been necessary for minimizing computing costs and maintaining the highest degree of precision in findings based on computational analysis. The minimum thermal gradient and minimum thermal flux are found in Al 6061, while the maximum thermal gradient and maximum thermal flux are found in Al6061/0.6Ninp/0.6Crnp (HNMMC1). There have been differences in thermal gradient and thermal flux at high temperature for the different percentage compositions of HNMMCs with reinforcements such as Ni and Cr nanoparticles to Al6061. According to the results of the experiments, the thermal conductivity of the hybrid nano metal matrix composites decreases as the wt.% of Ni with Cr increases. The thermal displacements of the different compositions of HNMMCs have also been decreased dramatically, increasing the thermal gradient of the hybrid composites. As thermal gradient is temperature dependent, the values of thermal displacement of the hybrid compositions are steadily decreasing in the calculation of the thermal gradient of the hybrid composites, increasing the thermal gradient.

However, when compared to other HNMMCs and Al6061, the thermal flux for HNMMC1 is high because the thermal conductivity of these hybrid composites gradually increases with the rise in temperature. Due to the addition of graphene, resulting in a difference in the net heat transfer rate. The thermal conductivity of HNMMC1 decreases as more Ni and Cr nanoparticles are introduced because they have lower thermal conductivity than Al6061. The evaluation of thermal properties, such as thermal flux and thermal gradient, may help realize the benefits of Al6061/0.6Ninp/0.6Crnp hybrid nano metal matrix composites in structural applications and identifying the temperature positions is critical to harm the interface.
Table 6. Contour plots for thermal flux and thermal displacement of HNMMCs and Al6061 for temperature range 50 °C–300 °C.
5. Conclusions

The thermal behavior of Al6061 hybrid nano metal matrix composites reinforced with Ni and Cr nano particles was studied. The following conclusions are drawn based on the thermal characterization of formed nano composites.

- The highest value of thermal conductivity is found in Al6061/0.6Ninp/0.6Crnp hybrid nano-metal matrix composites. At the same time, there is a decrease in thermal conductivity at maximum temperature for the different percentage compositions of HNMMCs with reinforcements such as Ni and Cr to Al6061 but higher than Al6061.

- Thermal conductivity initially increases due to the addition of graphene as it has a very high magnitude of thermal conductivity, further graphene wt.% kept constant for other developed HNMMCs. With variations in density, weight percent of Ni and Cr nano particles, and porosity of hybrid nano metal matrix composites, the thermal conductivity decreases over a wide temperature range.

- The maximum value of thermal gradient and thermal flux has been observed for Al6061/0.6Ninp/0.6Crnp (HNMMC1), while the minimum magnitude of thermal gradient and thermal flux has been observed for Al 6061.

- Thermal flux and thermal gradient directly correlate with the thermal conductivity of developed composites.

- It has been observed that experimental results, theoretical results, and FEA results agree with each other.

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Table 7. FEA and theoretical comparison for thermal flux (W m\(^{-2}\)) of Al6061 and HNMMCs.

| Temp(°C) | Al 6061 | HNMMC1 | HNMMC2 | HNMMC3 | HNMMC4 |
|----------|---------|--------|--------|--------|--------|
| 50       | 3652    | 4942   | 4663   | 4125   | 4124   |
| 100      | 11022   | 13215  | 12034  | 11495  | 11492  |
| 150      | 18392   | 20987  | 19408  | 18867  | 18863  |
| 200      | 25764   | 27964  | 26782  | 26242  | 26234  |
| 250      | 33136   | 35346  | 34162  | 33620  | 33614  |
| 300      | 40308   | 42729  | 41541  | 41000  | 40994  |

Theoretical results

| Temp(°C) | Al 6061 | HNMMC1 | HNMMC2 | HNMMC3 | HNMMC4 |
|----------|---------|--------|--------|--------|--------|
| 50       | 3650    | 4940   | 4663   | 4122   | 4123   |
| 100      | 11022   | 13214  | 12031  | 11495  | 11491  |
| 150      | 18388   | 20986  | 19405  | 18863  | 18858  |
| 200      | 25763   | 27964  | 26778  | 26242  | 26233  |
| 250      | 33135   | 35343  | 34160  | 33618  | 33612  |
| 300      | 40303   | 42724  | 41537  | 40997  | 40989  |

Table 8. FEA and theoretical comparison for thermal gradient (°C m\(^{-1}\)) of Al6061 and HNMMCs.

| Temp(°C) | Al 6061 | HNMMC1 | HNMMC2 | HNMMC3 | HNMMC4 |
|----------|---------|--------|--------|--------|--------|
| 50       | 51437   | 51826  | 51555  | 51615  | 51749  |
| 100      | 52005   | 52261  | 52199  | 52323  | 52408  |
| 150      | 52382   | 52998  | 52652  | 52745  | 52858  |
| 200      | 53105   | 53617  | 53269  | 53463  | 53369  |
| 250      | 53464   | 54257  | 53640  | 53689  | 53641  |
| 300      | 54678   | 54831  | 54382  | 54363  | 54236  |

Theoretical results

| Temp(°C) | Al 6061 | HNMMC1 | HNMMC2 | HNMMC3 | HNMMC4 |
|----------|---------|--------|--------|--------|--------|
| 50       | 51435   | 51821  | 51553  | 51611  | 51744  |
| 100      | 52000   | 52260  | 52195  | 52327  | 52405  |
| 150      | 52381   | 52997  | 52651  | 52742  | 52855  |
| 200      | 53103   | 53612  | 53265  | 53459  | 53367  |
| 250      | 53460   | 54253  | 53636  | 53684  | 53636  |
| 300      | 54077   | 54830  | 54377  | 54361  | 54232  |
Hence, Al6061 /0.6Ninp /0.6Crnp (HNMMC1) has a higher magnitude of thermal conductivity than other hybrid nano metal matrix composites and Al6061 in the chosen temperature range.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Conflict of interest

The authors declare no conflict of interest.

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