Nigerian Research Journal of Engineering and Environmental Sciences 4(2) 2019 pp. 903-911

Nigerian Research Journal of Engineering and Environmental Sciences
Journal homepage: www.rjees.com

Original Research Article

Development of Grey Cast Iron Exhaust Manifold Material with Enhanced Thermal Stability

***Adesokan, I.O., Aponbiede, O., Sheu, U. and Adebisi, A.A.**
Department of Metallurgical & Materials Engineering, Ahmadu Bello University, Zaria, Nigeria.
*ilanre15@yahoo.com

ARTICLE INFORMATION

Article history:
Received 07 Jun, 2019
Revised 20 Sep, 2019
Accepted 21 Sep, 2019
Available online 30 Dec, 2019

Keywords:
Exhaust manifold
Grey cast iron
Thermal fatigue
Thermal Conductivity
Casting

ABSTRACT

The high demand for environmentally friendly vehicles with improved properties such as low fuel consumption, high engine performance and low emission of toxic gases has led to the search for methods of improving the properties of exhaust manifold materials. The aim of this study is to develop grey cast iron exhaust manifold materials with nickel in the range 1-3% as alloying element in order to enhance its thermal stability at elevated temperatures. The test samples for this study were developed by alloying the grey cast iron material through sand casting by melting scrap grey cast iron manifold above it melting temperature before alloying it with nickel in the appropriate proportion. Hardness, fatigue and thermal test. Control samples were produced after melting the scrap grey cast iron manifold without the addition of nickel, and other test samples were produced by adding nickel in the proportion 1% Ni, 2% No and 3%Ni respectively. Thermal test carried out on the cast test samples are thermal conductivity, coefficient of thermal expansion and specific heat capacity tests. The results from the test carried out show that grey cast iron manifold material improved with the addition of 1-3 % nickel. The hardness value doubled between 2-3% Ni and also 2% Ni gave the best fatigue life compared to the control material. After the test, addition of 2% Ni addition to the grey cast iron material gave the best result.

1. INTRODUCTION

Exhaust manifold is a part of a combustion engine which is required to collect the exhaust gases from the cylinder head and transmits it to the exhaust system. The manifold is a cylindrical section supported by four cores, and the operating condition of the manifold is about 302 kg/hour flow rate of exhaust gas at a temperature of about 870 oC (Nikhil and Omkar, 2016). The exhaust manifold plays an important role in the performance of an automobile engine because the efficiencies of emission and the fuel consumption rate are related to the exhaust manifold performance (Agilesh and Pichandi, 2016). It is basically used in a multiple cylinder internal combustion (IC) engine which collects the exhaust gases from the cylinders into one pipe. During operation, it dissipates heat and emits harmful and undesirable substances like noxious or toxic gases (Saravanan *et al.*, 2017). It receives the high temperature gases from the cylinder exhaust ports with the least possible back pressure while keeping the exhaust noise at a minimum level. Whenever gas is pushed through the passage way, turbulence and friction along the sides of the passage cause a resistance which results to back pressure. The piston encounters back pressure each time it oscillates on the exhaust stroke which causes power loss (Saravanan *et al.,* 2017). A direct and unrestricted flow of exhaust gas causes less back pressure and also prevents loss of power. The exhaust manifold comprises of the exhaust pipes, silencer or muffler and the tail pipe. The exhaust gas temperature varies according to the power produced by the engine. The manifold is designed to sustain variation of thermal expansion in the material from idle to full power conditions where the highest temperature is produced (Mouna and Imran, 2012).

Over the years, automotive exhaust manifold systems have been the subject of changes in design and material. The reasons for these are categorized into four major areas: Exhaust temperature, start-up emissions, aspiration, and refinement (Dollet et al., 2016). The temperature range of an automobile exhaust system is around 600-850 °C. Therefore, materials to be used in manufacturing the exhaust system should be able to handle this temperature and still retain their mechanical properties (Durga *et al.*, 2015). Normally, materials used for this application are ferrous alloys which include carbon steel, stainless steel, alloy steels and cast iron (Vijay *et al.,* 2017). Mild carbon steel was extensively used for the manufacturing of exhaust systems for a considerable period of time. Although mild steel has the properties to withstand exhaust temperature but it has a very poor corrosion resistance. Moreover, higher demands in power and environmental safety have seen the demise of mild steel from exhaust systems (Charles *et al.*, 1996). Nowadays mild steel is employed in applications where the environment is non-corrosive. Stainless steel has replaced mild steel in exhaust systems today (Dollet *et al.*, 2016). The ferrous alloying element used here is chromium, but chromium is very expensive. Cast iron is the material of choice for 60- 70% of today's exhaust manifold market (Vijay *et al.,* 2017). While ductile cast iron will perform quite satisfactorily at temperatures up to 850 °C, beyond this temperature, the material yield strength reduces and therefore, the associated thermal expansion problems set in thereby making the material less attractive (Scandian and Boher, 2012). From literature, addition of alloying element such as copper, Chromium, Vanadium, Nickel to grey cast iron improves the material property (Sulardjaka *et al.*, 2013). Addition of nickel to grey iron increases its thermal stability iron at elevated temperature (Krause, 1969). Cracks are usually initiated at the tip of graphite flakes; therefore, the presence of nickel reduces the thickness of graphite flakes thereby reducing it susceptibility to thermal failure and crack at elevated temperature (Sulardjaka *et al.*, 2013).

Based on the highlighted studies, the influence of material plays a major role on the performance properties of the exhaust manifold. Therefore, the effect of alloying grey cast iron exhaust manifold with nickel at the range 1-3% was investigated in this study to ascertain its thermal stability.

2. MATERIALS AND METHODS

2.1. Materials

The material used for this study is grey cast iron produced from the exhaust manifold of a passenger car purchased from spare part local market in central market Ori Apata, Kaduna State, Nigeria. Other materials include pure nickel, wood pattern, moulding flask and sand.

2.2. Chemical Composition of Grey Cast Iron Manifold

The chemical composition was determined using Optical Emission Spectroscopy at the Nigeria Machine tools Osogbo, Osun State, Nigeria. A section part of the grey cast iron manifold was extracted to produce a specific dimension of 5×3× 20 mm with a thickness of about 20 mm. The section was placed on the machine. Profiling and sparking were subsequently carried out. The global iron programme was used for analysing the sample. Electrical energy was applied to the sample, the electrode generates sparks which makes a humming sound to indicate machine-specimen contact, sparking was done for about 90 seconds and subsequently flushing was done. The sparks result in vaporized atoms in a high energy rate within the discharged plasma. When the vaporized atoms reached the discharged plasma, it created a particular emission spectrum specific to each of the composition element of the sample. The resulting spectrum was then examined. The intensity of an element spectrum will vary in proportion to the amount of the element that is present in the test specimen. The procedure was repeated on three other samples, and average set of results were obtained and recorded accordingly. The procedure was repeated three times and an average composition was deduced.

2.3. Casting of the Test Samples

The melting and casting of the materials were carried out using an oil-fired crucible furnace at the National Automotive Design and Development Council (NADDC) Zaria, Kaduna State. The materials were heated until it was completely molten. It was then poured into the already prepared moulding flask to give rise to the test samples. Casting was done using sand casting method according to ASTM A48/A48M. Four different compositions were produced; one for the existing manifold as control samples, and the other for 1% Ni, 2% Ni and 3% Nickel addition respectively. The cast samples were then removed from the mould and surface finishing such as machining and cutting of the gating system was done on the cast samples.

2.4. Specific Heat Capacity Test

Specific heat capacity was carried out using method of mixture according to ASTM E129 standards. Some water was poured into a beaker and the sample piece was suspended in boiling water. The calorimeter and stirrer were weighed. The temperature of sample and that of boiling water were taken and the hot metal sample was quickly transferred into copper calorimeter containing a known mass of water. The mixture was stirred and the highest temperature reached by the mixture was recorded. The calorimeter was weighed again to determine the total mass of the mixture. The specific heat capacity of the sample piece was then determined using the following equations.

$$(M_1S_2+ M_1S_1)(\Theta_3 - \Theta_1) = M_2S_2 (\Theta_2- \Theta_3) \tag{1}$$

$$S_1 = \frac{M_1S_2(\theta_2 - \theta_1)}{M_1(\theta_3 - \theta_1)} - \frac{M_S}{M_1} \tag{2}$$

Where M_1 is the mass of the test sample, M_2 is the mass of the calorimeter and water, S_1 is the specific heat capacity of the test sample, S_2 is the specific heat capacity of the copper calorimeter, Θ_1 is the initial temperature of water in the calorimeter, Θ_2 is the temperature of the heated test sample and Θ_3 is the final temperature of the mixture.

The procedure was then repeated for all the composition and the specific heat capacity of each was calculated and recorded accordingly.

2.5. Thermal Conductivity Test

The thermal conductivity of the material was measured using Searle's apparatus. A space was made in the steam chamber equal to the cross-sectional area of the sample piece whose thermal conductivity was to be measured. One end of the sample was inserted into a steam chamber. A copper tube was coiled around the other end of the sample and a steady flow of water was maintained in the copper tube. Water entered into the tube at the end that was far away from the steam chamber and it left at the end nearer to it. Two holes were drilled in the sample piece and mercury was filled in these holes to measure the temperature of the rod at these two ends with the help of thermometers T_1 and T_2. Mercury was used so as to prevent any loss of heat from the sides. Thermometers T_3 and T_4 were provided to measure the temperatures of the outlet and inlet water. Steam was then passed into the steam chamber and a stream of water was maintained. The temperatures of all the four thermometers rose initially and ultimately became constant when the steady state was reached. The readings q_1, q_2, q_3, and q_4 were noted in steady state. The whole apparatus was well lagged with layers of an insulating material like wool so as to prevent heat losses to the environment. A beaker was weighed and the water coming out of the copper tube was collected in it for a fixed time, t measured using a stop clock. The beaker was then weighed along with the water that had been collected in it. The cross-sectional area of the sample was calculated and also distance between the holes in the sample piece using Equation 3.

$$K = \frac{xMs(\theta_3 - \theta_4)}{A(\theta_1 - \theta_2)t} \quad (3)$$

Where x= length of the rod between the holes, A= cross-sectional area of the sample piece, K= thermal conductivity of the sample piece, Θ_1 = initial temperature and Θ_2 = final temperature.

2.6. Linear Expansivity Test

Linear expansivity is the fractional increase in length of a specimen of a solid per unit rise in temperature. Test samples were machined to a length l_1, the initial temperature of the specimen θ_1 was measured and recorded. Heat was then applied until an appreciable increase to length l_2 was observed at temperature θ_2. Therefore, the specimen increased in length from l_1 to l_2 when its temperature was raised to θ°, then the expansivity (α) is given by $l_2 = l_1(1+\alpha\theta)$. This relationship assumes that α is independent of temperature. The coefficient of thermal expansion (CTE) was calculated using Equation (4).

$$\alpha = \frac{l_2 - l_1}{l_1(\theta_2 - \theta_1)} \quad (4)$$

Where l_1 = Initial Length, l_2 = final length, α = linear expansivity value of the sample piece, Θ_1 = initial temperature and Θ_2 = final temperature.

2.7. Hardness Test

The hardness test was carried out according ASTME E110 standards using the Indentec Universal hardness testing machine with model number 8187.5LKV. Rockwell hardness tester with HRC scale was used to measure the hardness of the material. Cast samples were grounded and polished. The test piece was mounted using Bakelite which provided good balancing on the hardness tester. The samples were then placed one after the other on the machine. A minor load of 10kg was initially applied and this took up the slack in the system and the dial indicator was set to zero. The major load of 150 kg was then applied and when the major load was taken off, the hardness value was displayed on the dial indicator. The hardness was taken on three different spots on each test piece. Three readings were obtained for each of the test sample compositions and the average value was recorded as the hardness value accordingly. The hardness test was then repeated for each of the compositions produced.

2.8. Fatigue Test

The fatigue test was carried out according to ASTM JIS 2774 standards using the fatigue testing machine (Sm 1090). After cooling, the specimen was then fitted in the tommy bar into the hole in the drive shaft, the small hexagonal key was used to loosen the screw at the top of the grim ball in order to fit in the test sample.

The tommy bar was then removed and the control was switched on. The appropriate dimensions were input on the system such as the neck diameter and load. The load arm was held up and the appropriate frequency was set. The speed control of the instrumentation unit was set to minimum (anti-clockwise). The adjustable dead weight was then moved along the load arm. The experiment was run until the test sample fractured. The experiment was repeated for all other compositions. The result was displayed on the monitor by plotting a graph of stress in MPa against the number of cycles to failure.

3. RESULTS AND DISCUSSION

3.1. Chemical Composition

The purchased exhaust manifold was made of grey cast iron because the amount of carbon present falls within the range of the percentage composition of grey cast iron as shown in Table 1. The silicon present was up to 3.9% which also promotes graphitization of the alloy and its amount present was within the grey cast iron silicon content (Vijendra, 2010). Moreover, the manganese present conforms to the composition of grey cast iron, while the amount of nickel present is 0.01% which can be concluded that nickel is present as a trace element. Finally, the composition falls within the range of chemical composition of grey cast iron used for automobile spare parts (Mikhailov, 1989).

Table 1: Chemical composition of an existing exhaust manifold

Status	Sample composition										
Element	%C	%Si	%S	%P	%Mn	%Cr	%Mo	%Ni	%V	%Cu	%Mg	%Fe
Amount	3.45	3.90	0.003	0.024	0.222	0.007	0.558	0.011	0.003	0.005	0.003	91.8

3.2. Effect of Nickel on Hardness

Hardness is defined as the ability of a material to resist indentation. The exhaust gases from the internal combustion engine passes through the manifold at high temperature and pressure. Therefore, the exhaust manifold material must be strong enough to withstand the high pressure of the hot gases. Figure 1 shows the hardness result of the existing manifold and the other three compositions produced.

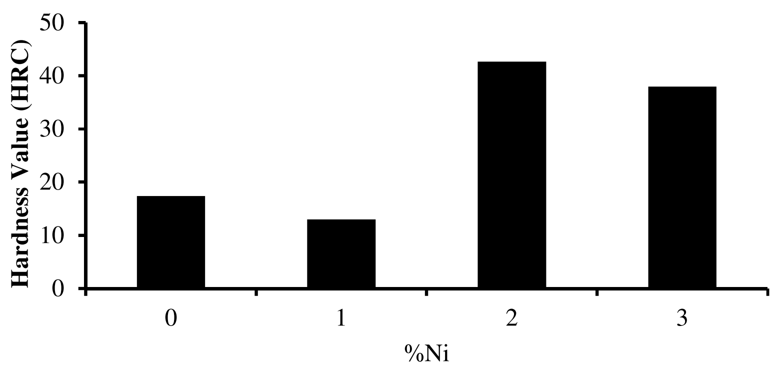

Figure 1: Hardness value (HRC) of test samples

From the results in Figure 1, it could be observed that the hardness of the material increased with over 200% in both 2% Ni and 3% Ni respectively and it decrease with about just 24% in 1%Ni when compared to the control material. The increase in hardness value observed is probably due to the presence of Ni which breaks up the cementite network and accelerates graphite formation (Vijendra, 2010). The 1%Ni addition to the grey cast iron material was observed to have a lower hardness value compare to the control material as well as 2%Ni and 3%Ni addition. Therefore, from literature survey it was reported that Nickel does not impair the hardness of grey cast iron (Sulardjaka *et al.,* 2013).

3.3. Effect of Nickel on Specific Heat Capacity

The result of the specific heat capacity is presented in Figure 2. Figure 2 shows the specific heat capacity of each of the material composition produced after the experiment. From the results, it could be deduced that the specific heat capacity of 1%Ni increased with 10 % while that of 2 %Ni increase with 16% and 3%Ni increase with almost 75% when compared with the control material. The increase in specific heat capacity could be attributed to the fact that nickel in grey cast iron reduces the thickness of graphite flakes thereby reducing the tendency to easily crack at elevated temperatures, since the tip of the graphite flakes are the major point where initiation of crack begins (Sulardjaka *et al.,* 2013). Therefore, it could be concluded that the higher the nickel content, the higher the amount of energy required to raise the temperature of the material by 1 ^{o}C of the material produced.

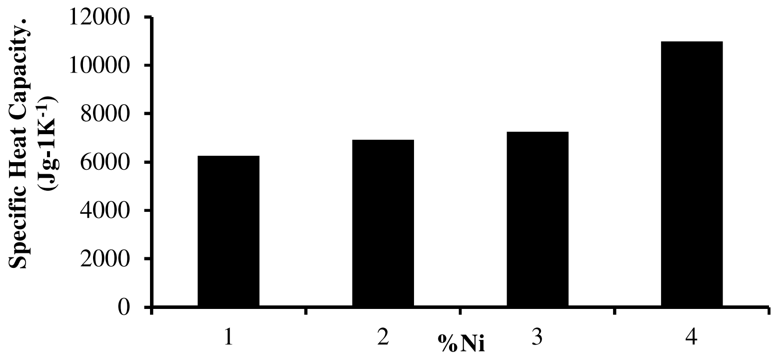

Figure 2: Specific heat capacity of the test samples

3.4. Effect of Nickel on Thermal Conductivity

The thermal conductivity test was carried out using Searle's apparatus. Several parameters were deduced such as the temperatures, mass and the cross-sectional area of the specimen. The thermal conductivity of the cast test samples was then calculated. The result of the thermal conductivity is represented in Figure 3.

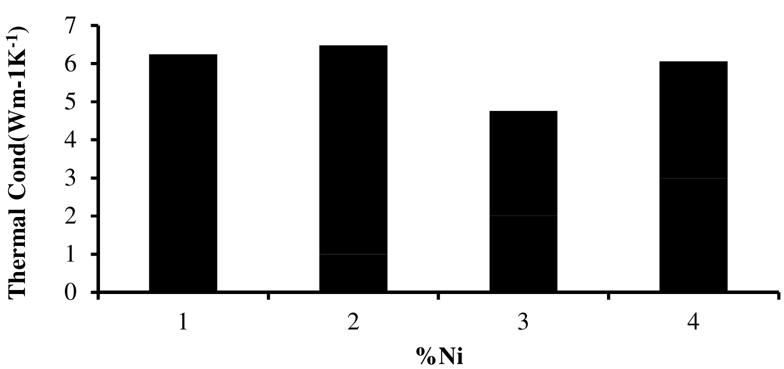

Figure 3: Thermal conductivity of the test samples

From the results in Figure 3, it could be observed that thermal conductivity of 1 %Ni increased by 12 %, while that of 2 %Ni decreased by almost 56% and 3 %Ni decreased by 51% when compared with the control sample. The higher the nickel content, the lower the thermal conductivity of the material (Stutzman, 1972). Therefore, increase in nickel content lowers the ability of the material to conduct heat because nickel in grey cast iron reduces the amount of combined iron present in the material (Krause, 1969). If a material conducts heat easily, it could easily undergo creep failure and if a material conducts heat less, it would not easily fail at elevated temperatures.

3.5. Effect of Nickel on the Linear Expansivity

The initial length of 10 cm was measured and the final temperature and length were measured and the graph obtained is presented in Figure 4. The values obtained were used to determine the linear expansivity of each of the samples.

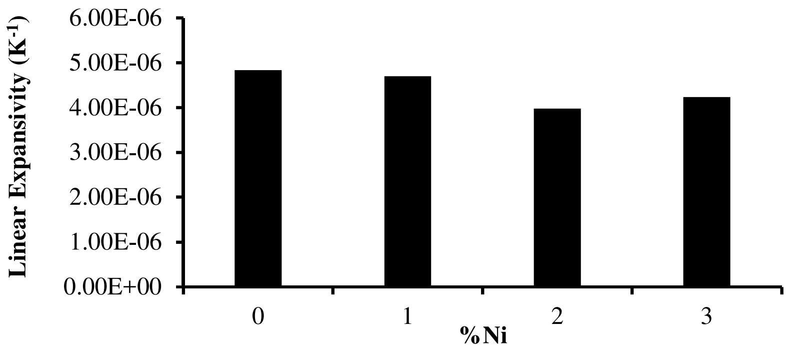

Figure 4: Linear expansivity of the test samples

From Figure 4, it was observed that the linear expansivity decreased with increase in Nickel content with the 1 %Ni sample reducing with almost 3%, and the 2 %Ni sample reducing by 18% and that of 3 %Ni decreasing by almost 12 % when compared with the control material. The reduction in CTE is due to the presence of nickel which breaks up the cementite network of the grey cast iron (Sulardjaka *et al.,* 2013). Therefore, since linear expansivity is defined as the fractional increase in strain per unit rise in temperature, then the higher the linear expansivity, the more the deformation of the material per unit increase in temperature. Since the addition of nickel decreases the linear expansivity, it could be inferred that increase in Nickel reduces the deformation of the material per unit increase in temperature (Sulardjaka *et al.,* 2013).

3.6. Fatigue Test

Figures 5-7 shows the results of the response of the test samples with a graph of stress in Mpa against number of cycles to failure for each composition produced. From the Figures 5-7, it was observed that as the nickel content increased, the number of cycles to failure also increased.; It could be observed that nickel affected the fatigue property of grey cast iron. Therefore, it was be concluded that addition of nickel increases the fatigue life of the material compare to the existing material (Sulardjaka *et al.,* 2013).

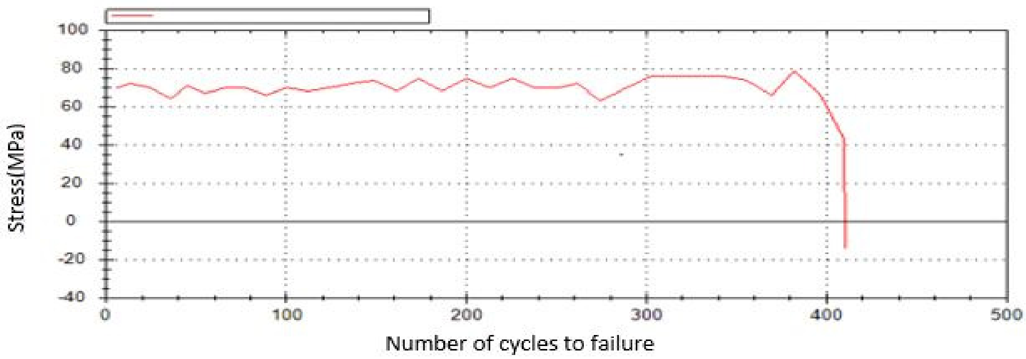

Figure 5: S-N curve for the control material

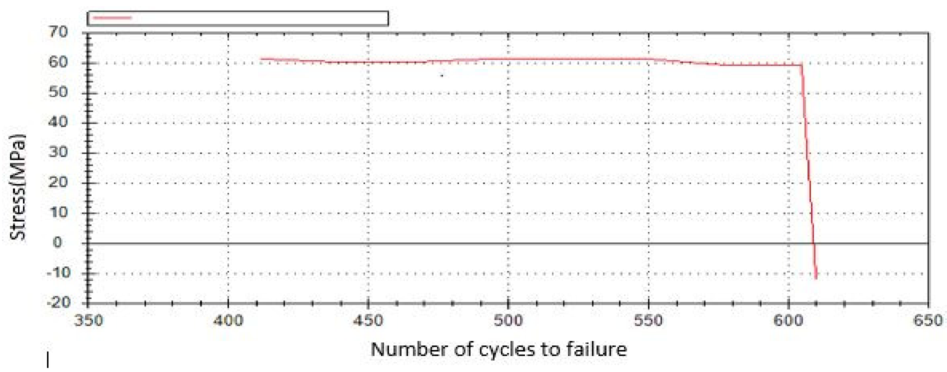

Figure 6: S-N curve for 1% Nickel material, showing stress

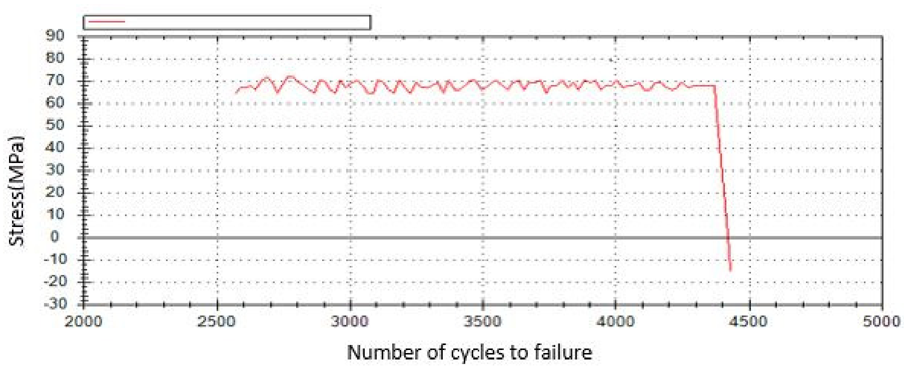

Figure 7: S-N curve for 2% Nickel material

4. CONCLUSION

The effect of addition of nickel to grey cast iron manifold material was investigated by adding nickel in the range 1-3 %. Thermal tests such as the specific heat capacity, linear expansivity, thermal conductivity test, and hardness test were conducted and from the result obtained it was observed that:

- The thermal properties of grey cast iron particularly the thermal stability at elevated temperatures increased with the addition of 1-3% nickel.

- Linear expansivity decreases with increase in Nickel content, but 2 %Ni has the least linear expansivity value at 3.98E-06 K^{-1}.
- The hardness value doubled between 2 to 3 % nickel addition: as compared with 1%Ni addition. The optimum 2% Ni is preferred because it gives a better fatigue life than the other compositions of grey cast iron
- The 2%Ni addition to grey cast iron for exhaust manifold casting is preferred for better performance.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

REFERENCES

Agilesh, A. and Pichandi, P. (2016). Design and Analysis of Exhaust Manifold in Diesel Engine. *International Journal for Research in Applied Science and Engineering Technology* (IJRASET), 4(3) pp. 634-640

Charles, H, F., Richard S, T., Lafrance J., and Hillebrand. D. (1996). The US Automobile Manufacturing Industry.

Dollet, S, R., Prakash, N. and, Ganesh, K, (2016). Design and Analysis of Exhaust Manifold Expansion Joint for WDP4D Diesel Locomotive. *International Journal of Mechanical and Production Engineering*, 4 (4), pp. 11-15

Durga, P, K., Sanmala, R, K., Mohan, K, J. and, Narayana, R.H. (2015). Thermal Analysis of Exhaust Manifold Coating with High Temperature Resistance Materials. *International Journal of Science Engineering and Advance Technology (*IJSEAT), 3(12). pp. 60-65

Krause, D.E., (1969). Grey Iron- A unique Engineering Material, Grey Ductile and malleable iron casting –current capabilities. *American Society for testing and materials Philadelphia* (ASTMSTP 455) pp. 3-28

Mikhailov A, M. (1989). *Metal Casting* Mir Publishers Moscow p. 166

Mouna, C. and, Imran, Q. (2012). Exhaust Manifold. *International Journal of Engineering Research & Technology,* 1(10), pp. 1-6.

Nikhil, K. and, Omkar, S., (2016). A Literature Review on Exhaust Manifold Design. *International journal of scientific research engineering & technology* (IJSRET), 5(5), pp. 286 – 288

Saravanan, J., Valarmathi, T, N., Rajdeep, N. and, Prasanth K., (2017). Experimental Analysis of Exhaust Manifold with Ceramic Coating for Reduction of Heat Dissipation. *Conference series Material Science and Engineering.*

Scandian, C., Boher, C., Melli, J, D. and Farhad, R., (2010) Effect of Molybdenum and Chromium Content in Sliding Wear of High-Chromium White Cast Iron. The relationship between microstructure and wear. *Wear,* 267 (1-4) pp. 401-408.

Stutzman, M., (1927). The effect of nickel upon the stability of Iron Carbide and on the microscopic structure of white cast iron composition. *Retrospective thesis and Dissertation*

Sulardjaka, S T., Atmadja. S., Nugroho, F., Adnan, A D, (2013). The effect of alloying element on fatigue strength of gray cast iron at room and high temperature. *Rotasi jurnal teknik Meson*, 15(1) pp. 23- 28

Vijay, G., Sahil, A., and, Nanak R. (2017). Design and Solidification Simulation of Exhaust Manifold made of SiMo Ductile Cast Iron ELK. *Asia pacific journals*, 978(93) pp. 6-12

Vijendra, S. (2010) *Physical Metallurgy.* 6th Edition.