

NICKEL AS AN ALTERNATIVE AUTOMOTIVE BODY MATERIAL

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ABSTRACT

The study of the thermal, chemical and mechanical properties of pure nickel as an alternative automotive body material is presented in this paper. Current automotive components mainly use steel as the body material. Due to the increasing demand for high performance and related issues, interest is moving towards alternative materials to steel. The hardness values of both heat-treated and non-heat treated pure nickel do not change after annealing; the hardness values are in the range of 118 to 123 HV. As the annealing temperature increases, the ultimate tensile strength, yield strength and Young's modulus decrease, which indicates that the ductility increases. The highest ultimate tensile strength of pure nickel at 300 °C annealed temperature is 758.78 MPa. X-ray diffraction (XRD) studies confirmed pure nickel as a face centred cubic (FCC) structure with a lattice constant measured as 0.3492 nm for the unannealed sample, which increases to 0.3512 nm for the annealed samples. The corrosion rate of both annealed and non-heat treated pure nickel is in the range of 0.0266 to 0.048 mm/year.

Keywords: Alternating material, nickel, annealing, corrosion resistance.

INTRODUCTION

Due to the increasing demand for high-quality exterior panels, better functional properties and lower weight in the automotive industry, much research has been conducted to find an alternative to the existing automotive body material; steel. One of the requirements of an alternative automotive body is weight reduction. This is because the weight of the automotive body will ultimately affect energy consumption. Every 56.69 kg of weight reduction results in a fuel economy gain of 0.09–0.21 km per litre. Therefore, lightweight materials are necessary to achieve fuel efficiency. Cui, Wang, and Hu (2008) stated that the automotive body and interior account for approximately 40% of the weight of an automobile. Therefore, automotive body materials have changed from steel to aluminium. However, conventionally the weight of the steel is greater than that of aluminium and the cost of steel is lower than aluminium. Apart from the weight of the material used for an automotive body, its mechanical properties are also important for increasing performance. Edwards (2004) stated that materials with properties of high specific stiffness and strength should be used for highly efficient lightweight load bearing structures. Whereas steel sheets with high strength and strain and transformation-induced plasticity should be used for body panels. The properties of alloy steel allow deep drawing; provide resistance to denting and offer the opportunity of using a lighter gauge in order to reduce vehicle weight. The material used in an automotive body should have the properties of high fracture toughness, which provides the capability of absorbing energy in the case of high-speed crashes.

Klarstrom (2001) stated that nickel and nickel-based alloys are important to modern industry because of their ability to withstand a wide variety of severe operating conditions involving corrosive environments, high temperatures and high stress. Nickel, a transition metal is ductile and tough because it possesses a face-centred cubic crystal structure up to its melting point. It is used for making stainless steel, low alloy steels and cast iron, etc. It is widely used in variety of applications: food-processing equipment, chemical shipping drums, battery manufacture, aircraft, gas turbines, caustic handling equipment and piping. Of the galvanic series of metals, nickel is one of least active elements, which means that the tendency of nickel to corrode is low. According to Rebak, Dillman, Crook, and Shawber (2001), nickel has good resistance to corrosion in the normal atmosphere, natural freshwater and deaerated non-oxidising acids and has excellent resistance to corrosion by caustic alkalis. Lee, Woo, Lee, and Han (2008) stated that the automotive body must fulfil mechanical performance requirements, such as deflection, stiffness and strength, in an extensive number of structural design considerations and components. Steel is the traditional automotive body material; however, the steel needs to be coated due to its corrosion potential when exposed to moisture (Davies, 2003). In this research, the thermal properties of pure nickel were obtained by annealing with different temperatures. Various tests have been conducted to obtain the mechanical, chemical, structural and other properties of pure nickel. The testing includes: tensile tests, microhardness tests, corrosion tests, structural analysis by using X-Ray Diffraction (XRD) and composition and morphology studies by scanning electron microscope (SEM) and Energy-dispersive X-ray (EDX) spectroscopy. This work presents comparative data of the mechanical and chemical properties of pure nickel and samples annealed at 300, 500 and 700 °C.

EXPERIMENTAL PROCEDURES

The characterisation of pure nickel is studied as an alternative automotive body material. The processes involve heat treatment, during which the annealing of pure nickel at various temperatures is performed, followed by mechanical and corrosion tests. Annealed and unannealed samples were prepared to dimensions according to the international ASTM and ASE standards (Kuroda, Kawasaki, Yamamoto, Hiromoto, & Hanawa, 2005). According to Tillack, Manning, and Hensley (1990), stress relieving of nickel ranges from 425–870 °C and therefore, three different annealing conditions at 300, 500 and 700 °C were chosen. Corrosion rates of pure nickel for both non-heat treated and annealed samples were determined by using the Eurocell Tafel extrapolation technique with GRES-DC 105 software. The samples of pure nickel were characterised for tensile properties, a hardness morphology study and corrosion test.

Mechanical studies on the tensile and hardness properties of both non-heat treated and annealed samples of pure nickel were performed using an Instron 5585 Universal testing machine (UTM) with a test speed in the range of 0.01~500 mm/min. A micro Vickers hardness tester (MITUTOYO HM-200) was used to test all samples. For the Vickers test, both diagonals were measured and the average value was used to compute the Vickers hardness (HV). The hardness number is based on the surface area of the indent, divided by the applied force, giving hardness units of kgf/mm². X-Ray Diffraction was used to determine the crystal structure of the specimens and to identify changes in the lattice constant of both non-heat treated and annealed pure nickel. SEM and EDX were used to observe the materials morphology in macro and sub-micron

ranges. In this report, EDX was used to confirm the composition of pure nickel in both the non-heat treated and annealed samples.

RESULTS AND DISCUSSION

Hardness Analysis

The hardness of non-heat treated and heat treated pure nickel was measured using a micro Vickers hardness tester. Pure nickel, annealed at temperatures of 300, 500 and 700 °C, does not have a large difference in terms of its hardness value. Figure 1 shows the indentation of a diamond in contact with the surface of the sample. For non-heat treated pure nickel, the hardness value is 123.6 HV, whereas for samples annealed at 300, 500, and 700 °C, the hardness value was 120.8, 118.7 and 120.5 HV, respectively, as shown in Figure 2.

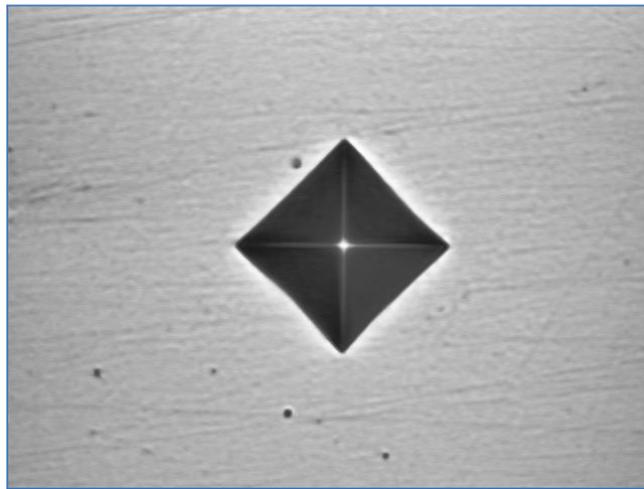


Figure 1. Indentation of diamond pyramid indenter with a 90° angle between opposite faces. Image is magnified 50×.

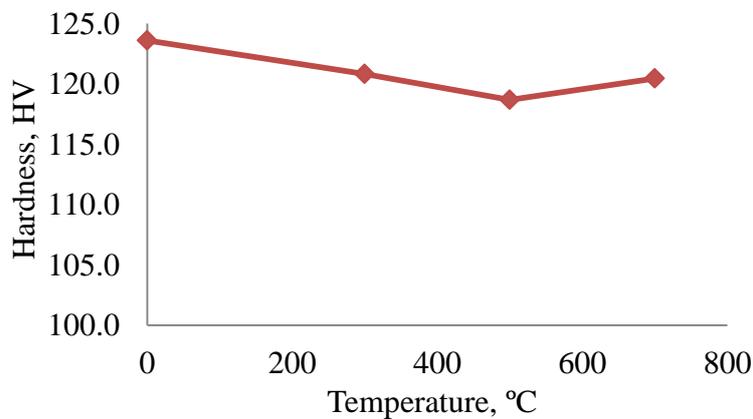


Figure 2. Hardness against annealing temperature.

The hardness of pure nickel with different annealing temperatures is shown in Table 1. There is no significant change in the hardness values of pure nickel with

different annealing temperatures for 1 hour. The range of hardness values for pure nickel at different annealing temperatures is 118–125 HV. According to the results obtained by Neishi, Horita, and Langdon (2002), the hardness for equal-channel angular pressing (ECAP) of pure nickel (99.99% purity), annealing at 1 hour decreased as the annealing temperature increased. Figure 2 shows the hardness value of ECAP of pure nickel (99.99%). The hardness value of pure nickel decreases to 100 HV as the annealing temperature increases. For an annealing temperature of 500 °C, the hardness value of the sample is 118 HV, which is in good agreement with previous studies (Neishi et al., 2002).

Table 1. Hardness of pure nickel with different annealing temperature.

Pure Nickel	Hardness values (HV)					Average
	1	2	3	4	5	
Non heat-treated	120.9	127.7	139.3	111.8	118.4	123.6
300°C- annealed	116.6	118.3	125.3	125.0	119.0	120.8
500°C- annealed	120.8	127.5	109.5	122.3	113.4	118.7
700°C- annealed	117.3	124.5	115	128.2	117.3	120.5

Tensile Analysis

A tensile test was carried out to obtain the tensile stress-strain behaviour of both non-heat treated and annealed pure nickel. Table 2 shows the mechanical properties (ultimate tensile strength, Young’s modulus and yield strength) of the pure nickel with different annealing temperatures. Figure 3 presents the ultimate tensile strength against different annealing temperatures of pure nickel. The ultimate tensile strength decreases as the annealing temperature increases. The highest ultimate tensile strength is 758.78 MPa measured for the sample heat treated at 300 °C and the lowest value is 368.07 MPa measured for the annealed sample at 700 °C. The yield strength at 0.2% offsets is determined by finding the intersection of the stress-strain curve with a line parallel to the initial slope of the curve, which intercepts the abscissa at 0.2%.

Table 2. Mechanical properties of pure nickel with different annealed temperatures.

Pure nickel	Ultimate tensile strength, (MPa)	Young’s Modulus (GPa)	Yield Strength (MPa)	Elongation, (%)
Non heat-treated	645.47	39.37	440	11.67
300 °C-annealed	758.78	30.67	530	14.54
500 °C-annealed	525.30	15.07	350	17.80
700 °C-annealed	368.07	15.60	240	12.36

Figure 4 presents yield strength against different annealing temperatures of pure nickel. The yield strength of 300 °C annealed pure nickel is higher than that of the non-heat treated pure nickel, the 500 °C annealed and the 700 °C annealed pure nickel. The yield strength is highest at 530 MPa for the 300 °C annealed pure nickel and lowest at 240 MPa for the 700 °C annealed pure nickel. The Young’s modulus is a measure of the stiffness of the material. A stiff material with a high Young’s modulus shows much

smaller changes in dimension when the applied stress is relatively small and only causes elastic deformation (Askeland & Phule, 2006).

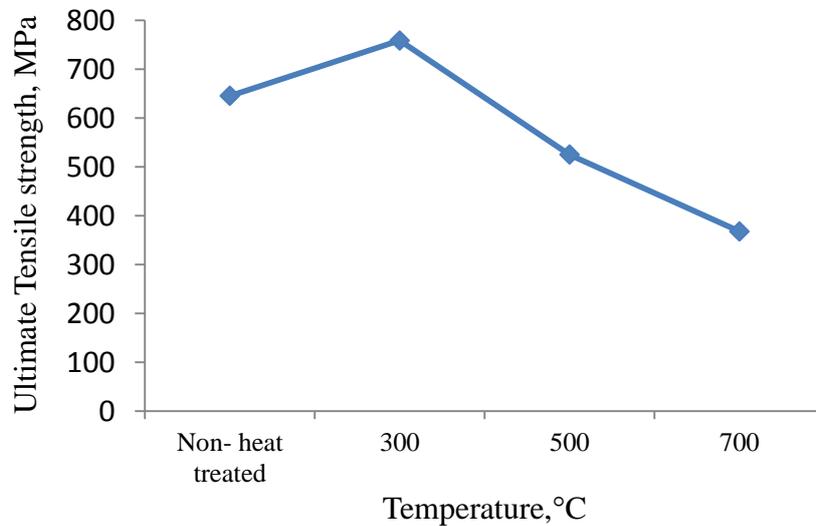


Figure 3. Ultimate tensile strength against different annealing temperature of pure nickel.

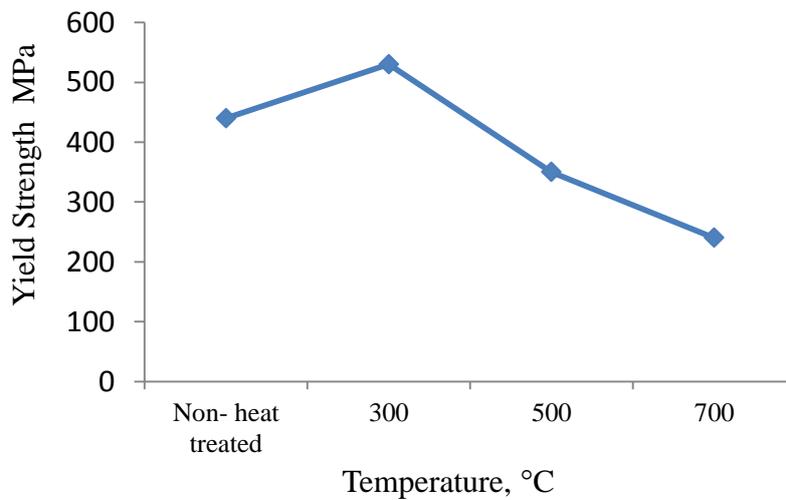


Figure 4. Yield strength against different annealing temperature of pure nickel.

Figure 5 presents the Young's modulus against different annealing temperature of pure nickel. The Young's modulus of non-heat treated pure nickel is the highest compared with annealed pure nickel. This indicates that non-heat treated pure nickel has greater stiffness compared with annealed pure nickel. The yield strength of 300 °C annealed pure nickel is higher compared with the high strength steel used in the automotive industry. The yield strength and ultimate tensile strength of non-heat treated and 300 and 500 °C annealed pure nickel is higher than forming grade. However, the yield strength and ultimate tensile strength of non-heat treated and 300, 500 and 700 °C annealed pure nickel are lower than for ultra-high-strength steel, titanium sheet, glass-reinforced plastic and carbon fibre composite. The ultimate tensile strength of ultra-

high-strength steel, titanium sheet, glass-reinforced plastic and carbon fibre composite is more than 924 MPa. The yield strength of ultra-high-strength steel, titanium sheet, glass-reinforced plastic and carbon fibre composite is more than 880 MPa. The cost of nickel (MYR/Kg) is higher than steel, aluminium and magnesium but lower than that of titanium alloy and composite. Therefore, pure nickel could act as an alternative automotive body material, replacing titanium and composite and in a few cases, steel.

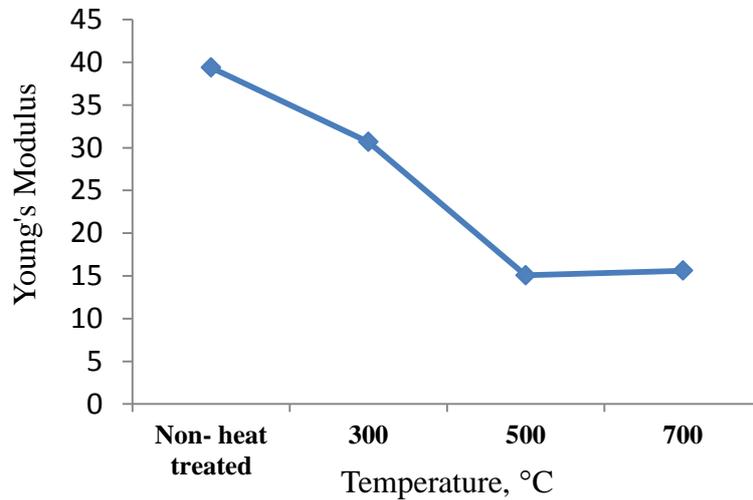


Figure 5. Young's modulus with different annealing temperature of pure nickel.

Corrosion Test

The Tafel extrapolation technique has been used to obtain the corrosion rate of nickel for various conditions of annealing temperatures. Figure 6 shows the corrosion of pure nickel for non-unannealed and annealed samples. The results of the corrosion analysis (corrosion current density and corrosion rate) using the Tafel extrapolation technique are tabulated in Table 3. There is no significant change in the corrosion rate of pure nickel at different annealing temperatures. The corrosion rate of 700 °C annealed pure nickel is the highest (0.048 mm per year) compared with the others. The corrosion rate of both 300 °C (0.0385 mm/ year) and 500 °C (0.0266 mm/ year) annealed pure nickel is lower than that of non-heat treated pure nickel and 700 °C annealed pure nickel.

Table 3. Corrosion analysis by using Tafel Extrapolation technique.

Pure nickel	Area in contact, cm	Density (g/cm ³)	Total anodic current, μA	Corrosion current density, A/cm ² (i _{corr})	Corrosion rate in 3.5% NaCl(mm/year)
Non-heat-treated	1.83	8.32	7.0	3.823	0.0440
300 °C-annealed	1.83	8.54	4.0	3.421	0.0385
500 °C-annealed	1.83	8.89	6.0	3.925	0.0466
700 °C-annealed	1.83	9.37	8.0	4.6852	0.0480

Corrosion resistance of automotive body material is an important parameter when considering its expected lifetime and maintenance. Nickel has good corrosion

resistance compared with aluminium, magnesium and iron. The rate of steel oxidation is higher and therefore, to improve the corrosion resistance of steel and to prolong automotive life, it is common to apply coated steel sheets to automotive body parts. There are various methods used for the protection of steel, such as zinc coatings, paint pre-treatments, electro-priming, wax injection and adhesives. According to Hayashi and Nakagawa (1994), the coated steel sheets have difficulty in press forming, such as surface damage of the plating layer, surface defects and unstable forming performance. Therefore, nickel is a good material for use as an alternative in automotive body parts due to its corrosion resistance.

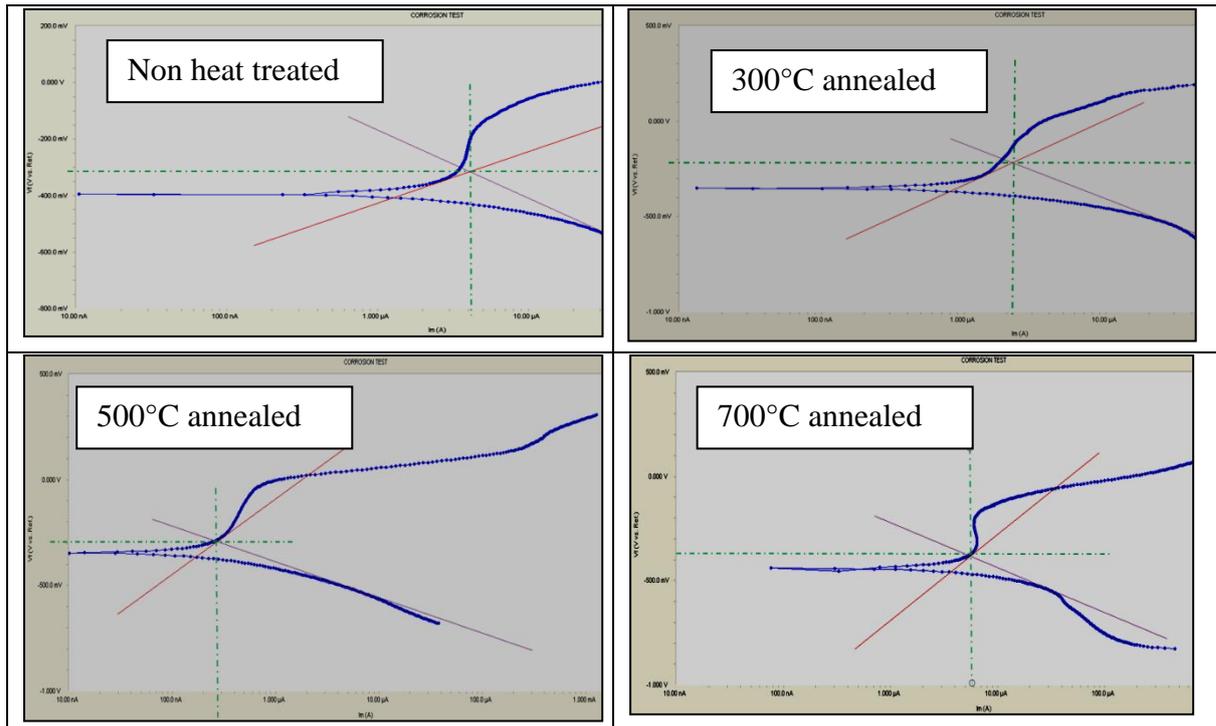


Figure 6. Tafel extrapolation of both non-heat treated and annealed nickel samples.

Energy Dispersive X-Ray Analysis

The purpose of using EDX is to identify the composition of both the non-heat treated pure nickel and the annealed pure nickel and the results are shown in Figure 7. It can be seen that the weight percentage and atomic percentage of non-heat treated and annealed pure nickel is not changed, which confirms that there are no impurities nor foreign elements present after heat treatment of the samples.

X-Ray Diffraction Analysis

The purpose of XRD is to identify the crystallographic changes of the non-heat treated and annealed pure nickel and the results are presented in Figure 8. By using the data obtained from XRD, the grain size of the pure nickel with different annealing temperatures can be calculated. The peak of pure nickel was determined from theoretical XRD lattice parameters, as shown in Table 4 with the comparison between

the theoretical and experimental interplanar spacing of the non-heat treated pure nickel sample.

Table 4. Theoretical XRD lattice parameter of pure nickel.

Pure nickel	Interplanar spacing d (dm)		Angle (2θ)	$(h\ k\ l)$	Intensity
	Theoretical	Experimental			
	0.2034	0.2020	44.505	1 1 1	100
Ni Cubic, $a = 0.3524$ nm	0.1762	0.1750	51.844	2 0 0	42
	0.1246	0.1242	76.366	2 2 0	21
	0.1062	0.1059	92.939	3 1 1	20
	0.1017	0.1015	98.44	2 2 2	7

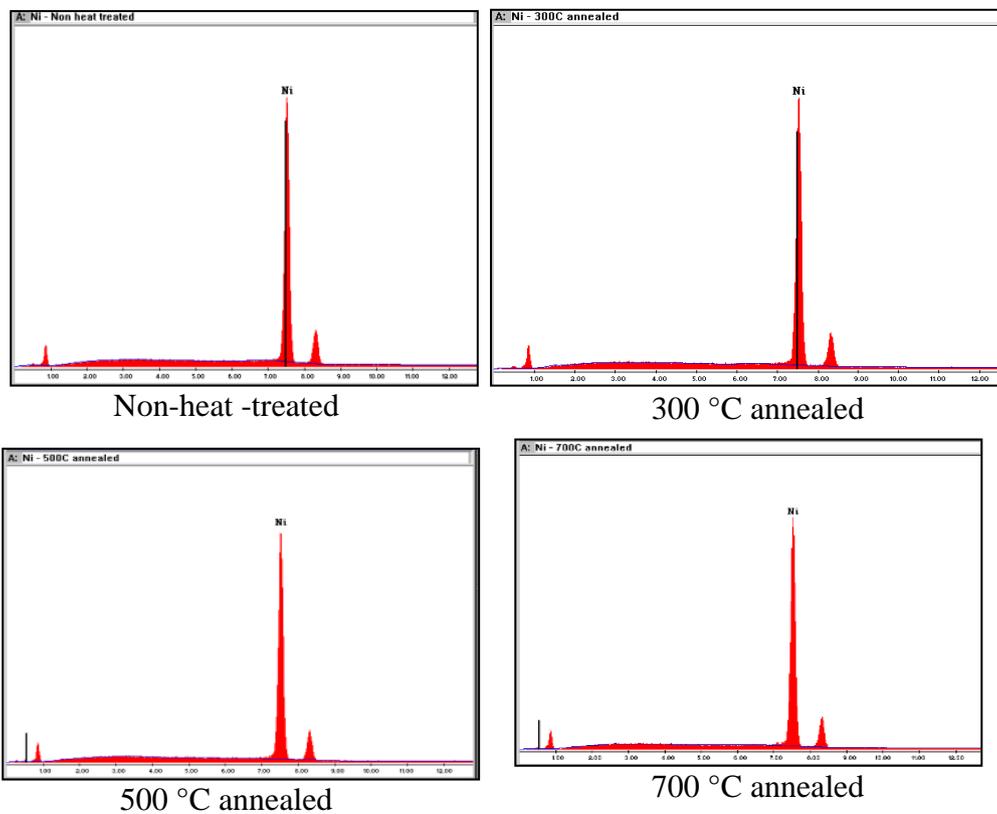


Figure 7. Compositional results obtained from EDX for non-heat treated and annealed pure nickel.

Table 5 shows the comparison lattice constant of both non-heat treated and annealed pure nickel in different peaks. The theoretical lattice constant for pure nickel is 0.3524 nm. The lattice constant is calculated from Eq. (1).

$$d_{hkl} = \frac{a}{\sqrt{h^2 + k^2 + l^2}} \tag{1}$$

where: a = Lattice constant; d = Interplanar spacing, nm; (h, k, l) = Miller indices.

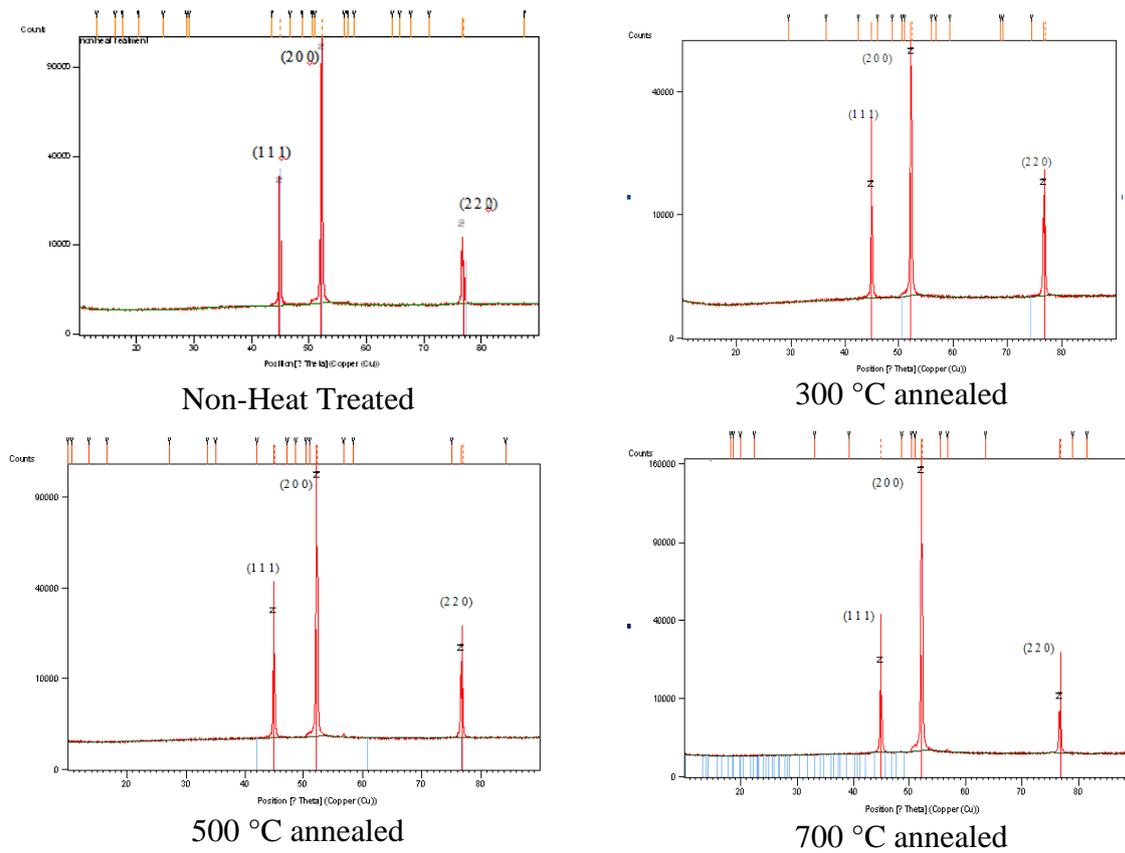


Figure 8. Crystallographic results obtained from X-Ray diffraction.

Table 5. XRD lattice parameters comparison (taking the (111), (200) and (220) - peak as reference.

Pure nickel	Lattice constant, <i>a</i>		
	(1 1 1)	(2 0 0)	(2 2 0)
Non-heat treated	0.3503	0.3502	0.3512
300 °C-annealed	0.3499	0.3500	0.3511
500 °C-annealed	0.3498	0.3496	0.3510
700 °C-annealed	0.3494	0.3492	0.3509

The crystallography of pure nickel was confirmed by XRD and it is confirmed as face centred cubic with the lattice constant in the range of 0.3492 to 0.3512 nm, which is almost the same as with the theoretical lattice constant, 0.3524nm. From Table 5, it can be seen that the lattice constant of pure nickel decreases as the annealed temperature increases. The grain size of pure nickel is calculated according to Eq. (2).

$$\text{Grain Size} = \frac{0.9\lambda}{B \cos \theta} \tag{2}$$

where: λ = wavelength
 B = peak width at half maximum in radians
 θ = half of the reported peak centric

Table 6 shows the range of grain sizes for both non-heat treated and annealed pure nickel. The grain size of annealed pure nickel increases as the annealing temperature increases. According to Xiao, Mirshams, Whang, and Yin (2001), the occurrence of abnormal grain growth in metals and alloys is generally related to the presence of a restraining force against grain growth. The typical restraining forces are second phase particles, free surface and crystallographic texture.

Table 6. The grain size range of non-heat treated and annealed pure nickel.

Nickel	Grain size range (nm)
Non heat-treated	0.6-2.7
300 °C-annealed	0.3-3.5
500 °C-annealed	0.5-4.4
700 °C-annealed	0.4-12.3

CONCLUSIONS

From XRD analysis, the lattice constant of non-heat treated and annealed pure nickel is in the range of 0.3492 to 0.3512 nm, which is in good agreement with the standard value of pure nickel (0.3524 nm). The grain size of pure nickel gradually increases for both non-heat treated and its annealed counterparts. The hardness of annealed pure nickel does not show major changes, which is in the range of 118–124 HV and temperature change does not affect the hardness. The yield strength and ultimate tensile strength of annealed pure nickel decreases as the annealing temperature increases. For 500 °C annealed pure nickel, the elongation is more prominent than for other samples. Therefore, 500 °C annealed pure nickel is more ductile compared with the other samples. The corrosion rate of 700 °C annealed pure nickel is greater than for the others; the lowest corrosion rate is for 500 °C annealed pure nickel. By comparing the characteristics of both annealed and unannealed pure nickel with the current automotive material, the tensile strength of pure nickel is higher compared with aluminium, magnesium and some of the steels. Pure nickel is ductile and has good toughness with an FCC structure, which makes it suitable as an automotive body material because it can also absorb energy in the case of high-speed crashes. The cost of pure nickel is higher than steel but lower than some of the materials currently used for automotive body parts, such as titanium alloy and composites.

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