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Treatment of Turbine Blades via Cr_2O_3-Ni5%Al System Using Plasma Thermal Spraying

Esraa H. Mouhson [1], Sufian H. Humeedi [2], Salih Y. Darweesh [3] and Adnan R. Ahmed [4]

[1] Salah-Alddin Education, Ministry of Education, Tikrıt, Iraq
[2] Physics Department, College of Science, Tikrit University, Tikrit, Iraq
[3] Physics Department, College of Education TuzKhurmatu, Tikrit University, Tikrit, Iraq
[4] Physics Department, College of Education for Pure Sciences, Tikrit University, Tikrit, Iraq

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ABSTRACT

A plasma thermal spraying method was used for the purpose of coating the pre-prepared surfaces of turbine blades. Chromium oxide (Cr2O3) was used as a matrix reinforced with a metal material of Ni-5%Al at rates of 10, 20, 30, 40 and 50. The cermet powders were stirred for one hour then used to coat bases of steel (316L). A spray distance of 8cm was applied, and the binding material of Ni-22%Cr-10%Al-1%Y was sprayed with a thickness of 100μm. Then, the reinforced matrix was sprayed with a thickness of 300–350μm and the final thickness of the samples prepared was 400–450μm. The samples produced were sintered at 900°C for an hour and a half and underwent a hardness test, which gave the best hardness of the samples after sintering at a reinforcement rate of 50% by 612Hv. The lowest porosity value for the above rate was obtained at 3.88%. The results of the adhesive strength gave a value of 31.5 MPa after sintering and at the same 50% reinforcement. The results of the scanning electron microscope (SEM) showed that there was weakness and cracking in the coating layers at the low reinforcement ratios. However, the mechanical and physical properties improved with the increase in reinforcement ratios to reach the highest value of 50%.

KEYWORDS

Adhesion force, ceramites, scanning electron microscope, Vickers hardness

CITATION

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1. Introduction

Thermal spraying techniques have occupied an advanced position in coating processes. They allow the use of a wide range of materials, starting from materials with low melting points to those with high melting points. These techniques require high accuracy and control of the parameters and conditions of coating, such as material feeding rate, air thrust and distance between the spray gun and the base in order to obtain coatings with good adhesive strength, as well as high synthetic and mechanical properties (Darweesh *et al.*, 2019). Thermal spraying techniques represent the most important methods used industrially in the surface oxidation of industrial supplies, especially in coating large pieces efficiently with high deposition rates. Some composites can be used for coating mixed with other materials or separately (Berndt *et al.*, 2003; Kucuk *et al.*, 2000). In surface engineering technology, coating is generally applied to create physical and mechanical properties for important classification and technical characteristics, such as acceptable performance service, cost reduction over time, the resistance of the specified surface to wear, reusing the corrosive part of the surface and the treatment of mechanical corrosion, such as pitting and thermal barrier (Sarikaya, 2005). The selection of cermet composite materials consisting of ceramic oxides with high melting temperatures, such as Al_2O_3, TiO_2, or ZrO_2, with additives from metal materials is called cermet. Cermet materials have physical properties that are common in ceramic and metal materials. They have high thermal and mechanical properties in various technological applications. In recent years, researchers have made a great effort to use these composites on a large scale in many electrical and thermal applications, which creates excellent barrier properties in thermal barrier coating, especially in jet engines, marine engines and gas turbines (Gibson, 2016). Composite materials are usually influenced by the properties of the materials involved in its synthesis that include the matrix and reinforcing phase. The matrix is usually represented by the continuous phase in composite material. It works to hold together elements and materials of reinforcement and bind the parts together to form a coherent synthetic system that can produce excellent mechanical properties, including increased toughness and light weight. Therefore, attention is paid to the production of composite materials as a substitute for traditional engineering materials, such as metals, alloys or polymers. Reinforcement materials strengthen the matrix. They may be ceramic, metal or polymeric materials in the form of powders, fibres or flakes (Ahmed *et al.*, 2020). Accordingly, different coating techniques are used. These techniques may include plasma spraying, wire arc spraying and high velocity oxy-fuel spraying. The coating is applied using these techniques to protect external surfaces from erosion and cracking. In this regard, titanium oxide is one of the most important ceramic materials that helps to protect surfaces because of its high protection features in terms of resistance to corrosion and wear (Abdulla *et al.*, 2020). Chromium oxide has a very high hardness level, in addition to its multiple applications in the field of ceramic materials due to its high strength, hardness and friction. Its melting point is also very high, and it works extremely well with many metals, such as iron, nickel and aluminium, as a protective layer against the effects of various loads (Hakan *et al.* 2008). The current research aims to identify a technique to treat the turbine blades used in electrical power plants where the surfaces develop corrosion and cracks due to being exposed to a high degree of evaporation. This study examines the synthetic and mechanical properties of the system used for coating those turbine blades.

2. Experimental Details

2.1. Raw Materials:

The binder was the powder Ni-22%Cr-10%Al-1%Y with a thickness

Corresponding Author: Salih Y. Darweesh 009647703978848, salih.younis@tu.edu.iq

of 100μm manufactured by Amdry 962, with a granular size of +53–106μm). The reinforcement material was Ni5%Al, manufactured by Metco 480NS, with a granular size of +45–90μm. The matrix was chromium oxide (Cr_2O_3) of thickness with reinforcement reaching 300–350μm manufactured by WISDOM with a granular size of +11–45μm.

2.2. Preparation Method:

The cermet composite was prepared by taking Cr_2O_3 as a matrix and nickel-aluminium (Ni5%Al) with different reinforcement ratios (10, 20, 30, 40 and 50%). The powders were then well stirred using an electric mixer for two hours. A first thermal treatment of the cermet composite powders was then performed before the coating process at 100°C for 30 minutes using a German electric furnace containing a thermostat. The coating bases were made of STAL Steel 316L type. Next, they were cut and grinded to the appropriate dimensions required to be placed in the sampling holder and washed with alcohol to remove any lubricants. A sandblast device produced by Amin Tech was used to increase the samples' surface roughness. The grain used for roughing was sand with five bar pressure and diameters ranging from 0.7mm to 1.6mm. After roughing was completed, the bases were prepared for the spraying process. The coating was applied to the bases using the thermal spray process by plasma with the METCO 3MB device of American origin. This technique was used to coat all the samples prepared. The spray gun generated an electric arc producing plasma. The arc moved between the water-cooled copper anode electrode and the cathode electrode made of tungsten, continuously injecting the arc with the initial gas mixture, which usually consists of argon or nitrogen and secondary gas (5–20%) of the initial gas that consists of helium or hydrogen. The gas mixture was ionised and plasma was formed. Secondary gases were used to increase the ionisation energy of the arc gas mixture and raise the plasma thermal content to produce higher temperatures at a lower energy level. Plasma is a conductive gas and sometimes referred to as the 'fourth state of matter'. Despite the high temperatures of plasma that can reach 10000°C or 30000°C, little heat is transmitted to the work piece, so it remains relatively cold. Spray parameters were selected through a series of tests to ensure layers of coating with good adhesive strength and specific thickness to qualify for the study of the physical properties of coating. Thermal treatment of samples resulting from plasma thermal spraying was also applied at 900°C for two hours. The spray parameters are shown in Table 1.

Table 1: The Parameters of Plasma Spraying

Parameter	NiCrAlY	TiO_2+Ni5Al
Gun Type	3MB METCO	**3MB METCO**
Argon flow rate (SCFH)	**80**	80
Hydrogen gas flow rate (SCFH)	**15**	15
Current (A)	**450**	500
Voltage (V)	**50**	55
Argon powder carrier gas	**30**	30
Powder feed rate (Lbs./Hr.)	**10**	25
Spray distance	**12**	8

3. Examinations and Tests

3.1. Hardness Test:

Vickers hardness was measured for the coated samples after grinding and polishing before and after the thermal treatments. The indentation used was a pyramidal diamond indenter with an angle of 136° between the opposite sides that applied a load of 100gm for 10 seconds. It was automatically lifted after the illumination of the light indicator at the end of the specified time. The dimensions of the impression in the two axes and in two perpendicular directions were calculated by considering five readings and calculating their arithmetic mean to find the value of hardness from the digital screen installed on the device directly. The following formula represents Vickers hardness (Shahdad *et al.*, 2007):

$$Hv=1.854\frac{P}{{d_{av}}^2} \quad (1)$$

where (H_V): Vickers hardness, (P): the load applied (gm) and d_{av}: the mean of the indenter diameter. The hardness was measured in several different areas of the sample, and the hardness of the edges and centre were calculated to obtain an approximate value of the hardness rate.

3.2. Porosity Test:

The presence of pores in thermal spray coating is one of the most important features of the coating. These pores affect the properties of the coating; therefore, it is necessary to know their ratio in the coating. The porosity test was performed by using samples of the coating layer after removing it from the matrix when performing the test. Archimedes' principle (immersion method) was adopted in the calculation of porosity ratio in accordance with standard specification no. ASTM-C 830 (Mohammed *et al.*, 2018), which includes the following steps:

- Drying samples of the composite material for 30 minutes using an electric furnace (Heraeus) at 75°C, then weighing the samples using a sensitive balance (±0.001mgm). This weight is called W_1.
- Immersing the samples in a container filled with distilled water for 24 hours, then weighing the samples saturated with water, heating them to 100°C, leaving them to cool then weighing them again. This weight is called W_2.
- Weighing the samples immersed and suspended in distilled water. This weight is called W_3.
- Calculating the ratio of open pores (P_o %) using the following equation (Mohammed *et al.*, 2018):

$$P_o\,\% = [\,(W_2 - W_1)\,/\,(W_2 - W_3)\,] \times 100 \quad (2)$$

3.3. Adhesion Test:

An adhesion test of the coating layer was performed using a tensile device with a maximum load of 1.5 Ton, in accordance with the standard technical specification (ASTM - (C 633)) [10]. The following steps were followed when performing the test:

- Preparing the samples of the matrix without coating in a number equal to the unsprayed samples with the same standard dimensions.
- Performing chemical cleaning using alcohol for both unsprayed and sprayed samples in order to remove the effects of pollutants that obstruct the process of adhesing the two pieces together.
- Using the adhesive (epoxy) to fix the two samples together (unsprayed and sprayed), putting a regular thin layer of adhesive on the coating surface to cover the area, then pressing the two pieces together for approximately two hours. After that, putting them in a drying furnace for 24 hours at 50°C. Prior to the tensile experiment, regular adhesion is necessary, and the tensile force applied when performing the test should be completely vertical on the coating surface.
- Applying tensile load to each test sample at a tensile rate (1mm/min) until the sample failed as the highest load applied is recorded.
- Calculating the adhesion or cohesion strength of the coating on the composite material using the following equation (Swain *et al.*, 2020):

$$\text{Adhesion Force} = \frac{F}{A} \quad (3)$$

3.4. Scanning Electron Microscope Test:

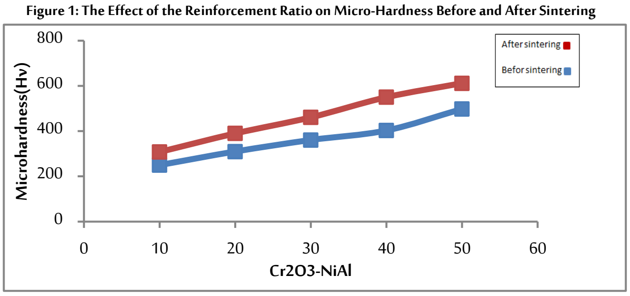
The scanning electron microscope consists of an electron generator that produces the electrons required to run the microscope, two convex lenses and an object lens as in an optical microscope are used to obtain a clear and detailed map (the only difference is that these lenses are not glass but made from a magnetic material capable of changing the path of electrons and controlling them). All this is carried out in a vacuum chamber to avoid the effect of air particles on the electrons. There is also a sample chamber, where the sample is placed to be examined so it is isolated from vibrations, because the microscope is very sensitive to motion. For this reason, it is usually placed on the ground floor of the laboratory. It has a sensor that reveals how electrons and samples interact and another sensor that records the movement of secondary electrons emitted from the sample surface. There are also X-ray sensors that allow researchers to obtain information about the composition of samples of elements called EDS, giving the microscope a 3D image of the sample with the smallest details. Handling this device is relatively easy, and the data and surface topography can be collected in no more than five minutes (Reimer, 2013).

4. Results and Discussion

4.1. The Effect of Reinforcement Ratio on the Micro Hardness:

Figure 1 shows the effect of the metal reinforcement ratio on the micro-hardness of the metal-based system before and after the thermal sintering process. It can be observed that at the low reinforcement ratios, hardness was low due to high porosity at these ratios. In the case of high reinforcement ratios, hardness will be high where porosity is as low as possible. Prior to the thermal treatment, the hardness of the steel base (316L) was calculated and found to be 233Hv. When applying plasma thermal spraying, the values of hardness were calculated and found to increase with the rise in oxide reinforcement ratios, reaching the highest value of 498Hv at the ratio of 50% NiAl. When performing the thermal treatment at 900°C for two hours, the values of hardness increased, reaching the highest value of 612Hv at the same ratio as above. It improved the hardness due to the low ratio of pores and the effect of nickel that has high hardness, thus improving the properties of the coating layer as a result of the sintering process and spreading that increased the strength of mechanical binding between the cermet coating layer and the base metal. In addition, the binder layer had a significant effect on the improvement of the mechanical properties of the system (Kumar *et al.*, 2020; Riyadi *et al.*, 2020). The relationship between porosity and hardness is a clear inverse relationship, as increasing the percentage of porosity will negatively affect the prepared models and the hardness value will decrease. This depends largely on the homogeneity and binding strength of the surface because the increase in porosity on the surface acts in the form of gaps, which in turn are considered superficial defects that reduce the binding between the ceramitic components.

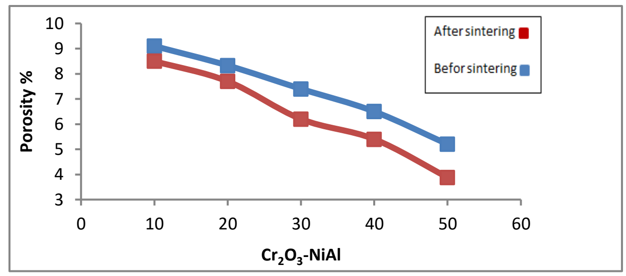
Figure 1: The Effect of the Reinforcement Ratio on Micro-Hardness Before and After Sintering



4.2. The Effect of Reinforcement Ratio on Porosity:

Porosity is one of the distinctive features determining the strength and weakness of the cermet layer through the ratios of open pores within the coating. It was tested in this study and the results are shown in Figure 2, which represents porosity before and after the thermal treatment (sintering). It was found that the use of low reinforcement ratios produces high porous values for the coating layer that gradually decrease with the increase of the metal part (NiAl) until it reaches 50% NiAl, the ratio that gave the lowest porous ratio, which is 5.2% before thermal treatment. The reason for high porosity may be the inability of molten droplets to fully flatten and connect with other droplets due to the high cooling rate experienced by the droplets during their spread that results from heat withdrawal to the base. Therefore, the droplets will suffer from thermal contraction after solidification (Ahmed *et al.*, 2020; Darweesh, 2014). When performing the thermal treatment of the cermet coating layers, it was observed that the porous ratio was lower than before the thermal treatment, reaching the lowest ratio at 50% NiAl, which is 3.88%. This means that sintering leads to the adequate rate of atoms spread to form new binding areas between layers through the movement of atoms between them in an attempt to close pores (Dahham *et al.*, 2020).

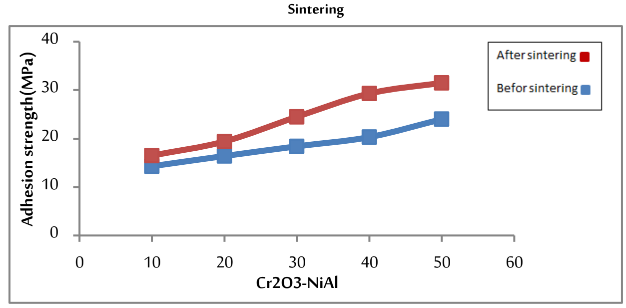
Figure 2: Changes in Porosity Ratios with Reinforcement Before and After Sintering



4.3. The Reinforcement Ratio Raises the Adhesion Strength:

Adhesion strength refers to the binding strength between the base surface and the cermet coating layer. The results of testing these samples show a value of 24 MPa adhesion strength before the thermal treatment and 31.5 MPa after the thermal treatment of the samples for two hours at 900°C. Figure 3 shows that adhesion strength is low when the ratio of the binder is low and this strength gradually increases as the ratio of the binder increases, until reaching the highest value of adhesion strength at the ratio 50% NiAl. This decrease is caused by the binder creating areas of correlation between the atoms of the coating material and itself at the expense of the adhesion strength between the coating layer and the base. When applying the thermal treatment of samples at 900°C for two hours, the value of the adhesion strength increased because the temperature reduced the porosity of the coating layer, increasing both hardness and adhesive strength accordingly (Sabard *et al.*, 2020; Abd Razzaq, 2019).

Figure 3: The Relationship of the Adhesion Strength with the Ratio of the Additive Before and After Sintering



4.4. Compositional Properties with Changing Ratios of Reinforcement by SEM:

Changes in adding the metal powder (Ni-5Al%) as a reinforcement material to (Cr_2O_3) were studied by using an SEM. Images were taken at different depths (μm) to identify the most important characteristics and features of the surface after the thermal sintering of samples prepared by plasma thermal spraying. Figure 4.a shows an SEM image of Cr_2O_3, which shows that the powder used is a homogeneous spherical shape and has no significant impurities. Figure 4.b shows an SEM image of the powder of the binder (Ni5%Al), which is a mixture of nickel (95%) and aluminium (5%).

In this regard, both nickel and aluminium are highly homogeneous and there is a distribution and spread between them. This shows that the powder used is spherical, indicating the purity and homogeneity of the two powders. Therefore, the homogeneity with the reinforcement material is greater when performing the process of thermal spraying by plasma, because the impurities work on placing interfaces, which also increases porosity ratios within the surface and weakens the samples. The results on the surface of the samples are very clear, as the sintering process has a significant effect on the recrystallization and fusion of the atoms that make up each surface, which helps to improve the mechanical properties of the samples.

Figure 4: SEM Image (a) Cr_2O_3, (b) Ni5%Al

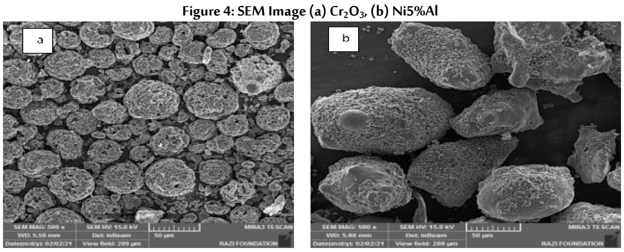
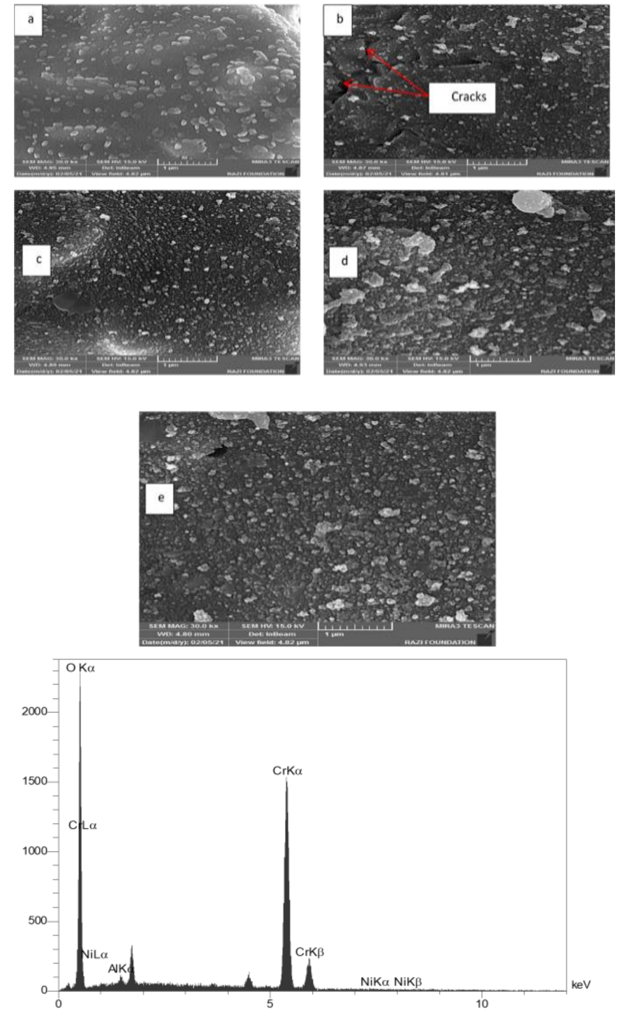


Figure 5 presents an SEM image of sprayed samples after sintering at 900 °C for two hours. Figure 5.a represents an image of coating by reinforcement of 10% NiAl. The bonding material is completely distributed within the matrix, but this layer suffers from weakness in the coating as the surface shows heterogeneity due to the low ratio of bonding material (Ni-Al). The bonding material increases the binding of oxide to the surface at a high temperature, which means that the bonding material is sufficient to form molten areas on the base and then generate areas of chemical interactions that increase the strength of adhesion (Darweesh *et al.*, 2019). Figure 5.b shows an image of coating at the reinforcement ratio of 20% NiAl. There appear to be cracks on the coating surface due to the low ratio of bonding material, which leads to the lack of homogeneity. However, Figure 5.c shows the coating layer reinforced by 30%NiAl. The increase in reinforcement ratios leads to an improvement in the coating layer and approximate disappearance of cracks. Figure 5-d shows a reinforcement by 40% NiAl, and there is a homogeneous distribution of composites to the surface of chromium oxide. In addition, the SEM image demonstrates a great homogeneity of the surface. This change in surface improvement is caused by the formation of correlation areas between the cermet coating layers following the processes of sintering and the spread of atoms as they attempt to close pores when performing thermal treatment, due to the increase in bonding material (NiAl). Figure 5.e presents the SEM image of reinforcement material (50% NiAl). It shows a clearly defined distribution of both the matrix (TiO_2) and reinforcement material (Ni-5% Al), demonstrating the semi-complete disappearance of cracks and pores within the cermet surface (50% Cr_2O_3-50%NiAl). This means that the surface becomes homogeneous and consistent with the bonding material (dark areas). Additionally, there is a spread and alloying correlation between the components of the stirred cermet composites. This means that the adhesion strength is low when the ratio of the bonding material is low, and this strength increases gradually as the ratio of the bonding material increases until reaching the highest value of adhesion strength at the ratio of 50% of the bonding material (Darweesh *et al.*, 2019). When observing Figure 5, we can see that there are significant differences between each concentration, which indicates that the addition of the metal part has changed the structure of the prepared models and improved both physical and mechanical properties.

Figure 5: SEM and EDS Image of the Cermet Composite (Cr2O3-%Ni-5%Al) Where: (a) 10% NiAl, (b) 20% NiAl, (c) 30% NiAl, (d) 40% NiAl, (e) 50% NiAl



5. Conclusions

The current research shows that the plasma thermal spraying technique produces a cermet composite layer of Cr_2O_3 based matrix reinforced by particles of nickel-aluminium powder (Ni5%Al) as a binder with good adhesion on the alloy base of St.St. 316L. After the coating process and sintering at 900°C for two hours, increasing the ratio of the reinforced binder (Ni5%Al) in the composite material layer to 50% reduces porosity and increases hardness. Therefore, the coating layer has excellent properties. Adhesion strength between the base surface and the composite material layer also improves with an increase in the ratio of reinforcement material to 50%. The SEM results also reveal a clear homogeneity and cohesion between the cermet composites as evidence of the binding strength of materials used, including Cr_2O_3 and the binder of nickel-aluminium. The strength of homogeneity and the absence of defects, especially at 50% of Ni-5%Al is evidence of improved compositional structure of the prepared samples.

Biographies

Esraa H. Mouhson

Salah-Alddin Education, Ministry of Education, Tikrıt, Iraq, maldoury93@gmail.com, 009647705669067

Mrs. Mouhson is an Iraqi teacher. She obtained a master's degree in Physics in 2018 from the Physics Department, College of Education for Pure Sciences, Tikrit University, Iraq. Her main field of interest is Physics of Materials. She has completed many research and scientific activities through participating in Tikrit University conferences and publishing research with the same specialty. She participated in the 2018 Crete University Conference, as well as many Physics Department's activities, such as courses and seminars.

Sufian H. Humeedi

Physics Department, College of Science, Tikrit University, Tikrit, Iraq, sufianhh@yahoo.com, 009647702797851

Mr. Hamidi has been an Iraqi teacher since 2011. He obtained a master's degree in 2004 from the Physics Department, College of Education for Pure Sciences, Tikrit University, Iraq and attended several local and international seminars in the field of physics. He has had a number of research studies published locally and globally. He has also had many articles dealing with physics in general and physics of materials in particular published in various journals.

Salih Y. Darweesh

Physics Department, College of Education Tuzkormato, Tikrit University, Tikrit, Iraq, salih.younis@tu.edu.iq, 009647703978848

Dr Darweesh is Iraqi. He obtained a doctorate in physics from the Physics Department, College of Education for Pure Sciences, Tikrit University, Iraq in 2018. Also, the researcher has published many papers within scopes containers as well as at the local level, has participated in many conferences in Iraq and other countries and is currently the head of the physics department at the College of Education, Tuzkormato, Tikrit University, Iraq. The researcher has had many articles published in the field of material physics and in magazines within Scopes, as well as supervising postgraduate students.

Adnan R. Ahmed

Physics Department, College of Education for pure Sciences, Tikrit University, Tikrit, Iraq, amazon9797@yahoo.com, 009647701217821

Dr Ahmed, PhD (Tikrit University), is an Iraqi. He has participated in several international and local conferences. He is currently supervising several postgraduate students working on physics related subjects at the University of Tikrit, in addition to those who were awarded their degrees.

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