

Manufacturing and analysis of carbon fiber knee ankle foot orthosis

Ayad M. Takhakh ^{1*}, Saif M. Abbas ²

¹Al-Nahrain University, College of Engineering, Mechanical Engineering Department, Iraq

²Al-Nahrain University, College of Engineering, Prosthetics and Orthotics Engineering Department, Iraq

*Corresponding author E-mail: ayadmurad@nahrainuniv.edu.iq

Abstract

Knee ankle foot orthoses (KAFOs) are used by paraplegia patients with low level spinal cord injury and having well control of the stem muscles. Four layers of carbon fiber with C- orthocryl lamination resin are used for manufacturing the knee ankle foot orthoses in this work. The mechanical properties of most of the components materials were estimated with the aid of fatigue and tensile test machines. Results of the tensile tests showed that the mechanical properties: yield stress, ultimate strength and modulus of elasticity were 92MPa, 105.7MPa and 2GPa respectively. The value of amidst pressure between the patient limb and the manufactured KAFO was measured using (F-socket) Mat scan sensor and these values of pressure were (663kPa) and (316kPa) for the thigh and calf regions respectively.

Keywords: KAFO; Carbon Fiber; Tensile Test and Interface Pressure.

1. Introduction

KAFOs are considered as good a treatment for patients with hamstring weakness, severe knee extensor, knee flexion spasticity and structural knee instability. The KAFO's components are foot, thigh upright, a proximal thigh band, ankle and knee joint. The KAFO's are manufactured of metal-metal, plastic-metal and composite materials designs.[1]. Many articles dealt with patients suffering from cerebral vascular accidents, neuromuscular deficiencies, quadriceps weakness and other cases [2-6]. Other articles studied the biomechanical effects, rehabilitations and engineering design of stance control knee-ankle-foot orthosis [7-16].

In general the KAFOs part are manufactured usually of composite materials, due to their high strength to weight ratio specification, [17-21], therefore, the composite materials are modified through the years by adding of different components, variable number of laminated layers, [22-23], reinforcement types and volume fraction, [24-26], in addition to, variable number of reinforcement materials (powder and fiber reinforcement), [27-30]. Then, due to the modification of the mechanical properties of composite materials, the applications are multitasked with various engineering parts, one of its application is Prosthetic and Orthotics, [31-40]. Where, at 2012, Muhsin J. Jweeg et. al, [31], investigated the creep and fatigue characterizations of Prosthetic Socket Below Knee with various layer laminated materials effect. Then, at same year, Bashar A. Bedaiwi et. al, [32], investigated the vibration behavior of its part with various laminated layer effect. At 2013, Ayad M. Takhakh et. al, [33], studied the vibration behavior of knee ankle foot orthosis with effect of different materials, as plastic and metal materials. Therefore, at 2014, Jumaa S. Chiad, [34], investigated the impact behavior of prosthetic lower limb with different laminated effect. After this, at 2017, Muhsin J. Jweeg et.al, [35], investigated the effect of cutout on the stress behavior of Syme's Prosthetics with different composite materials layers types. Also, at same year, Zainab Yousif Hus-

sien et. al, [36], studied the Ultraviolet Radiation effect on the fatigue characterizations of below-knee sockets with and without heat influence. In addition, at same year, Mohsin Abdullah Al-Shammari et.al, [37], presented study of mechanical properties for composite materials used in manufactured of Knee Prosthesis Sockets, in addition to, studied the stress analysis of its parts with various composite materials properties. Finally, at 2018, Ayad M. Takhakh, [38], and Jawad K. Oleiwi et. al, [39], studied the partial foot prosthetic with different parameters effect.

Therefore, from presented researchers it can be concluded that the reinforcement types effect on the mechanical behavior of the parts, then, can be modifying the straight and mechanical behavior of KAFO by variable reinforcement types of composite material used. In addition, from presented papers it can be shown that the numerical techniques or experimental techniques can be used to evaluate the mechanical behavior of KAFOs part with different effects, due to an agreement of results evaluated by its technique, [41-47].

Thus, since the experimental technique is perfect tool, therefore it can be used to evaluate the mechanical properties and behavior of application mechanical parts, [48-49]. The main objective of this experimental study is manufacturing of KAFO using composite material reinforced by carbon fiber and comparing of the mechanical properties with the traditional Polypropylene metal - plastic KAFO type. Also an assessment of the manufactured KAFO with measuring of the interface pressure by F-Socket device will be done. In addition, evaluating the fatigue characterizations of composite materials manufactured to application of KAFO part.

2. Experimental work

Carbon fiber composite materials orthosis, as shown in the Fig. 1, will be made of four layers carbon fiber and the C-orthocryl lamination resin which is the matrix. The thigh section, shank and foot are made of composite materials, while the uprights side bars was made of stainless steel then it will be covered by single layer of

carbon fiber. Knee joint system, ankle joint system are made from stainless steel.

The patient age, height and weight were 31 years, 1.85 m and 86 Kg respectively. Previously he used a KAFO manufactured of carbon fiber-metal in his left lower extremity suffering from Poliomyelitis, as shown in the Fig. 2. The tensile and fatigue tests samples were made using vacuum device, Fig. 3. These samples was manufactured of 4 layers of carbon fiber and the C-orthocryl lamination resin as a matrix.

The composite materials used in this work are compared with conventional material used in the manufacturing of KAFO and other orthoses i.e. Polypropylene in metal - plastic type which has good physical properties and kind of poor mechanical properties [50], while Carbon fiber composite material has better mechanical and environmental properties.



Fig. 1: The Manufactured KAFO.



Fig. 2: The Patient Wearing KAFO.



Fig. 3: Vacuum Method.

The tensile test specimens were made according to the ASTM standards ; the tensile specimen's geometry and dimensions for standard ASTM D638-I were specified for composites material (four layers of carbon fiber with C-orthocryl lamination resin) as shown in Fig. 4.

An alternating bending fatigue machine was used with constant amplitude in order to perform the fatigue test. Fatigue test specimen before test is presented in Fig. 5, it was 10 mm width and 100 mm length, [51]. The fatigue performance of a material is determined by testing a number of similar test specimens at different levels of maximum stress. Eight level stresses are used to apply the fatigue test with stress ratio ($R = -1$).

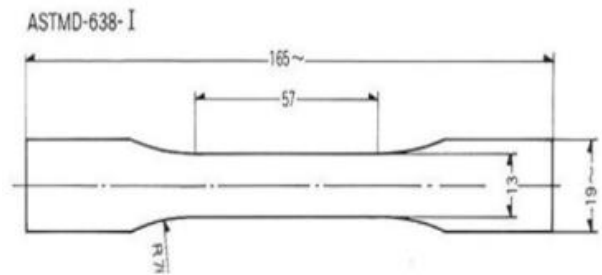


Fig. 4: The Tensile Specimens, 3.5 Mm Thick.

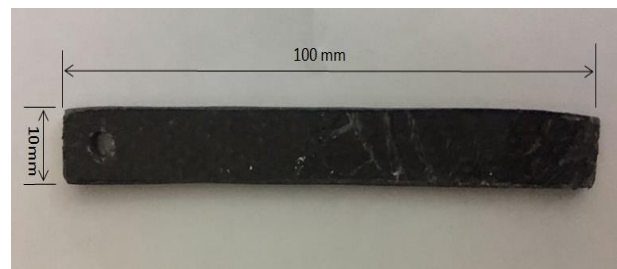


Fig. 5: The Fatigue Specimen.

The pressure between the thigh and calf regions was measured using F-Socket sensor. The used sensor was linked into a multi-meter to measure the pressure magnitudes resulted from the response through the stance phase. F-Socket sensors are interfaced with the computer in order to record the required data. Interface pressure test for patient wearing a KAFO at the calf and the bands of the thigh is shown in Fig. 6.



Fig. 6: Interface Pressure Test.

3. Results and discussion

The mechanical properties of four layers carbon fiber with C-or-thocryl lamination resin are listed in Table 1. Fig. 7 showed the stress-strain curve of carbon fiber.

Table 1: Mechanical Properties of Composite Material KAFO

KAFO Material	t (mm)	σ_y (MPa)	σ_{ult} (MPa)	E (MPa)	ρ (g/cm ³)
Carbon fiber (4-layer)	3.5	92	105.7	2	1.9
Polypropylene, [52]	/	/	28-41	1.3	0.9

t: Thickness (mm) for sample.

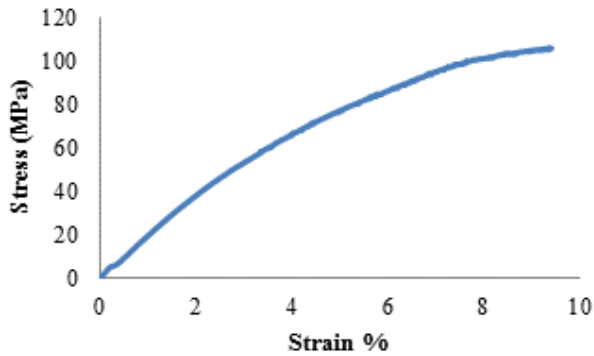


Fig. 7: Stress-Strain Curve of Carbon Fiber Composite Material.

Table I and Fig. 7 showed that there are large differences in the values of ultimate stresses and modulus of elasticity between the carbon fiber composite and polypropylene plastic materials, which were increased by more than 156% and 54% respectively as compared with Polypropylene.

These values if increments were attributed to the presence of the carbon fibers that have higher mechanical properties and stiffness than polypropylene (which its tensile resistance depends on the time, temperature, and loading).

The fatigue failure of the flat specimens occurs when the specimen fractures under alternative loading. The fatigue tester machine giving the number of cycles when the specimens were fractured recorded the readings. The S - N curve of carbon fiber composite material is shown in Fig. 8. Fig. 9 explained the S-N curve for Polypropylene, [50]. The samples fatigue life is corking in composite materials reinforced by carbon fibers comparing with that using polypropylene. The increase in the life time will reduces the cost of KAFO worn by the patient who used the orthosis permanently. The endurance limit of the composite and polypropylene materials were 65 MPa and 24.8 MPa at 106 cycle respectively, which was increased by about 162%. This results were attributed to the enhancement of mechanical properties due to using carbon fiber instead of the polypropylene.

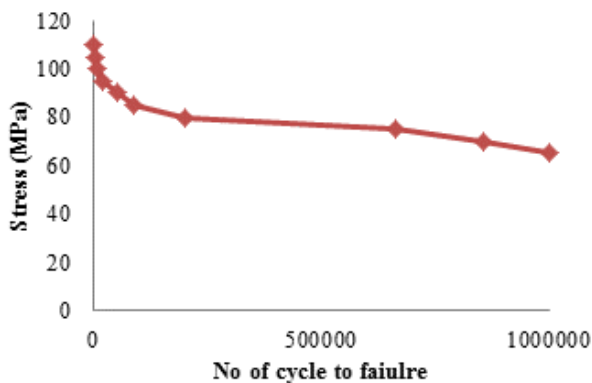


Fig. 8: S-N-Curve for (4 Layers of Carbon Fiber Composite Material).

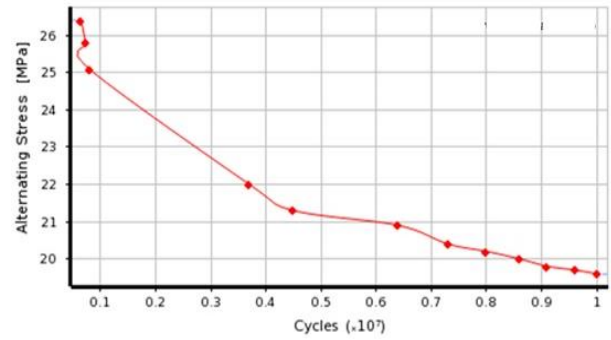


Fig. 9: S-N-Curve for Polypropylene. [50].

The interface pressure magnitude between the patient leg and the manufactured KAFO was measured by the F-Socket sensor. The sensor was connected with a computer program (F-Scan) to obtain the pressure curve applied to the sensor. The pressure was estimated in calf and thigh regions at the posterior side of the leg. The results showed that the maximum magnitude of muscles pressure on the orthosis is shown at the top region and it goes slightly to a lower value on going to the bottom as listed in Table 2 and shown in Figs. 10 and 11. The reason of this behavior is that the thigh muscles have more activity as compared with the calf one. This is due to the disability of the patient BK region and the weakness of his leg (upper region). Area and force distribution of the thigh region are shown in Figs. 12 and 13. The area and force distribution of the thigh region are shown in Figs. 14 and 15.

Table 2: Values of Interface Pressure for KAFO

KAFO Regions	Thigh	Calf
Interface Pressure kPa	563	316

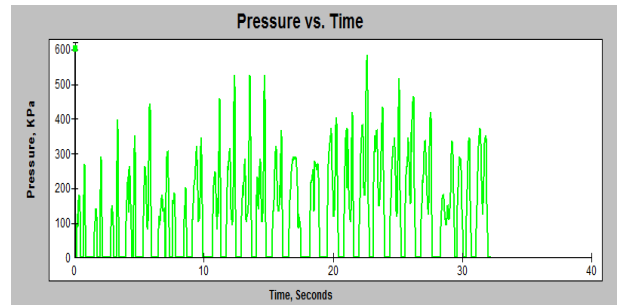


Fig. 10: Interface Pressure vs. Time at Thigh Region.

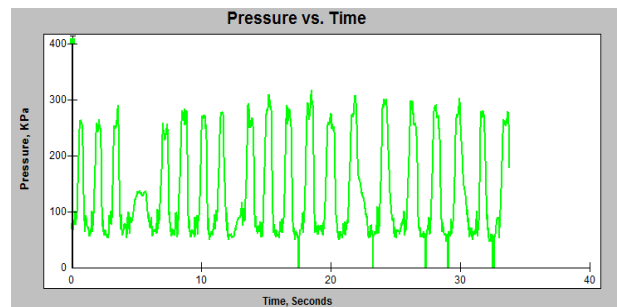


Fig. 11: Interface Pressure vs. Time at Calf Region.

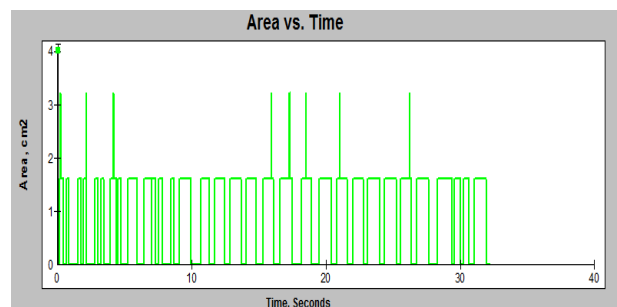


Fig. 12: Area vs. Time at Thigh Region.

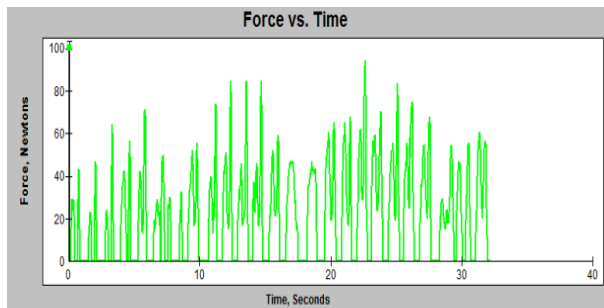


Fig. 13: Force vs. Time at Thigh Region.

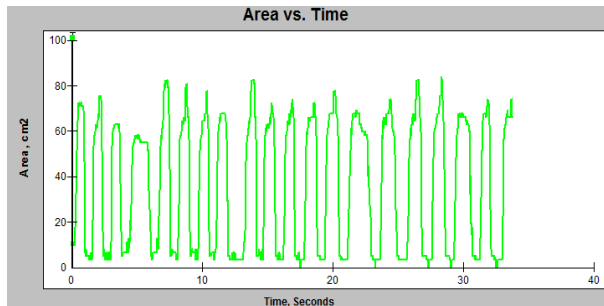


Fig. 14: Area vs. Time at Calf Region.

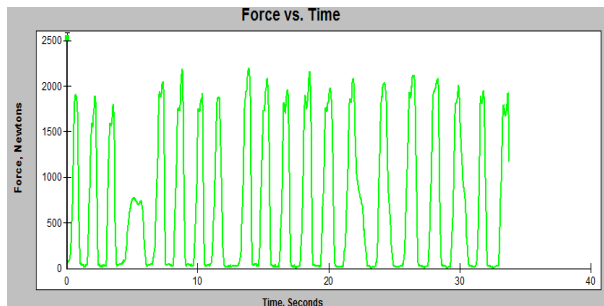


Fig. 15: Force vs. Time at Calf Region.

4. Conclusion

- 1) The results of the mechanical properties (σ_{ult} and E) showed that the KAFO made of 4 layers of carbon fiber with C-orthocryl lamination resin were increased by 156% and 54% respectively as compared with that made of Polypropylene. This increment was attributed to the inclusion of the carbon fibers which have higher mechanical properties and stiffness than polypropylene.
- 2) The endurance limit of carbon fiber composite is increased by about 162%. The reason was attributed to the mechanical properties of the used composite material which are higher than those of the polypropylene.
- 3) The results showed that the maximum interface pressure is recorded at the thigh region with a value of 563 kPa and it is decreased gradually in the calf region with a value 316 kPa.

Acknowledgment

The authors would like to express their gratitude to the Prosthetics and Orthotics Engineering Department at College of Engineering at Al-Nahrain University, Iraq.

References

- [1] Louise Baxter & Stephen Peebles 'Patient information about knee ankle foot Orthoses' Cambridge University Hospitals NHS Foundation Trust, 2009.
- [2] W. Robert and M. Leslvie 'A physiologic rationale for orthotic prescription in paraplegia' Clin. Prosthet. Orthot. Vol. 11, No. 2, pp. 66–73, 1987.
- [3] E. A. Hurley 'Use of KAFOs for patients with cerebral vascular accident, traumatic brain injury, spinal cord injury' J. Prosthet. Orthot. Vol. 18, No. 7, pp. 199–201, 2006. <https://doi.org/10.1097/00008526-200606001-00009>.
- [4] M. K. Taylor 'KAFOs for patients with neuromuscular deficiencies' J. Prosthet. Orthot. Vol. 18, No. 7, pp. 202–203, 2006. <https://doi.org/10.1097/00008526-200606001-00010>.
- [5] J. E. Earl, S. J. Piazza, and J. Hertel 'The protonics knee brace unloads the quadriceps muscles in healthy subjects' J. Athletic Train., vol. 39, no. 1, pp. 44–49, 2004.
- [6] C. Slemenda, K. Brandt, D. Heilman, S. Mazzuca, E. Braunstein, B. Katz, and F. Wolinsky 'Quadriceps weakness and osteoarthritis of the knee' Ann. Internal Med., vol. 127, no. 2, pp. 97–104, 1997. <https://doi.org/10.7326/0003-4819-127-2-199707150-00001>.
- [7] J. B. Redford, J. V. Basmajian, and P. Trautman 'Orthotics: Clinical Practice and Rehabilitation Technology' New York: Churchill Livingstone, 1995.
- [8] S. Irby, K. Bernhardt, and K. Kaufman 'Gait of stance control orthosis users: The dynamic knee brace system' Prosthet. Orthot. Int., vol. 29, no. 3, pp. 269–282, 2005. <https://doi.org/10.1080/03093640500238915>.
- [9] S. Irby, K. Bernhardt, and K. Kaufman 'Gait changes over time in stance control orthosis users' Prosthet. Orthot. Int., vol. 31, no. 4, pp. 353–361, 2007. <https://doi.org/10.1080/03093640601076909>.
- [10] B. Zacharias and A. Kannenberg 'Clinical benefits of stance control orthosis systems: An analysis of the scientific literature' J. Prosthet. Orthot., vol. 24, no. 1, pp. 2–7, 2012. <https://doi.org/10.1097/JPO.0b013e3182435db3>.
- [11] T. Yakimovich, E. Lemaire, and J. Kofman 'Engineering design review of stance-control knee-ankle-foot orthoses' J. Rehabil. Res. Develop., vol. 46, no. 2, pp. 257–267, 2009. <https://doi.org/10.1682/JRRD.2008.02.0024>.
- [12] R. Waters, J. Campbell, L. Thomas, L. Hugos, and P. Davis 'Energy costs of walking in lower-extremity plaster casts' J. Bone Joint Surg. Am., vol. 64, no. 6, pp. 896–899, 1982. <https://doi.org/10.2106/00004623-198264060-00013>.
- [13] S. Hwang, S. Kang, K. Cho, and Y. Kim 'Biomechanical effect of electromechanical knee-ankle-foot-orthosis on knee joint control in patients with poliomyelitis' Med. Biol. Eng. Comput., vol. 46, no. 6, pp. 541–549, 2008. <https://doi.org/10.1007/s11517-008-0310-6>.
- [14] B. Phillips and H. Zhao 'Predictors of assistive technology abandonment' Assist. Technol., vol. 5, no. 1, pp. 36–45, 1993. <https://doi.org/10.1080/10400435.1993.10132205>.
- [15] K. R. Kaufman, S. E. Irby, J. W. Mathewson, R. W. Wirta, and D. H. Sutherland 'Energy-efficient knee-ankle-foot orthosis: A case study' J. Prosthet. Orthot. vol. 8, no. 3, pp. 79–85, 1996.
- [16] Nadire Berker & Selim Yalcin, "The Help Guide to Cerebral Palsy" Second Edition. Merrill Corporation' Washington, 2010, pp: 49.
- [17] Muhsin J. Jweeg, Ali S. Hammood, Muhannad Al-Waily 'Experimental and Theoretical Studies of Mechanical Properties for Reinforcement Fiber Types of Composite Materials' International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS, Vol. 12, No. 04, 2012.
- [18] Muhsin J. Jweeg, Ali S. Hammood, Muhannad Al-Waily 'A Suggested Analytical Solution of Isotropic Composite Plate with Crack Effect' International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS, Vol. 12, No. 05, 2012.
- [19] Mohsin Abdullah Al-Shammari, Muhannad Al-Waily 'Theoretical and Numerical Vibration Investigation Study of Orthotropic Hyper Composite Plate Structure' International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS, Vol. 14, No. 06, 2014.
- [20] Ameer A. Kadhim, Muhannad Al-Waily, Zaman Abud Almalik Abud Ali, Muhsin J. Jweeg, Kadhim K. Resan 'Improvement Fatigue Life and Strength of Isotropic Hyper Composite Materials by Reinforcement with Different Powder Materials' International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS, Vol. 18, No. 02, 2018.
- [21] Mohsin Abdullah Al-Shammari, Muhannad Al-Waily 'Analytical Investigation of Buckling Behavior of Honeycombs Sandwich Combined Plate Structure' International Journal of Mechanical and Production Engineering Research and Development (IJMPERD), Vol. 08, No. 04, pp. 771–786, 2018.
- [22] Muhsin J. Jweeg, Sameer Hashim Ameen 'Experimental and theoretical investigations of dorsiflexion angle and life of an ankle-Foot-Orthosis made from (Perlon-carbon fibre-acrylic) and polypropylene materials' 10th IMEKO TC15 Youth Symposium on Experimental Solid Mechanics, 2011.
- [23] Saif M. Abbas, Ayad M. Takhakh, Mohsin Abdullah Al-Shammari, Muhannad Al-Waily 'Manufacturing and Analysis of Ankle Disar-

- tication Prosthetic Socket (SYMES)' International Journal of Mechanical Engineering and Technology (IJMET), Vol. 09, No. 07, pp. 560-569, 2018.
- [24] Luay S. Al-Ansari, Muhannad Al-Waily, Ali M. H. Yusif 'Vibration Analysis of Hyper Composite Material Beam Utilizing Shear Deformation and Rotary Inertia Effects' International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS, Vol. 12, No. 04, 2012.
- [25] Ahmed M. Hashim, E. K. Tanner, Jawad K. Oleiwi 'Biomechanics of Natural Fiber Green Composites as Internal Bone Plate Rafted' MATEC Web of Conferences, 2016.
- [26] Muhannad Al-Waily, Alaa Abdulzahra Deli, Aziz Darweesh Al-Mawash, Zaman Abud Almalik Abud Ali 'Effect of Natural Sisal Fiber Reinforcement on the Composite Plate Buckling Behavior' International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS, Vol. 17, No. 01, 2017.
- [27] Muhsin J. Jweeg, Muhannad Al-Waily, Alaa Abdulzahra Deli 'Theoretical and Numerical Investigation of Buckling of Orthotropic Hyper Composite Plates' International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS, Vol. 15, No. 04, 2015.
- [28] Muhannad Al-Waily, Zaman Abud Almalik Abud Ali 'A Suggested Analytical Solution of Powder Reinforcement Effect on Buckling Load for Isotropic Mat and Short Hyper Composite Materials Plate' International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS, Vol. 15, No. 04, 2015.
- [29] Abdulkareem Abdulrazzaq Alhumdany, Muhannad Al-Waily, Mohammed Hussein Kadhim Al-Jabery 'Theoretical and Experimental Investigation of Using Date Palm Nuts Powder into Mechanical Properties and Fundamental Natural Frequencies of Hyper Composite Plate' International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS, Vol. 16, No. 01, 2016.
- [30] Muhannad Al-Waily, Kadhim K. Resan, Ali Hammoudi Al-Wazir, Zaman Abud Almalik Abud Ali 'Influences of Glass and Carbon Powder Reinforcement on the Vibration Response and Characterization of an Isotropic Hyper Composite Materials Plate Structure' International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS, Vol. 17, No. 06, 2017.
- [31] Muhsin J. Jweeg, Kadhim K. Resan, Mustafa Tariq Ismail 'Study of Creep-Fatigue Interaction in a Prosthetic Socket below Knee' ASME International Mechanical Engineering Congress and Exposition, 2012.
- [32] Bashar A. Bedaiwi, Jumaa S. Chiad 'Vibration Analysis and Measurement in the Below Knee Prosthetic Limb: Part I-Experimental Work' ASME 2012 International Mechanical Engineering Congress and Exposition, Proceedings (IMECE), 2012.
- [33] Ayad M. Takhakh, Fahad M. Kadhim, Jumaa S. Chiad 'Vibration Analysis and Measurement in Knee Ankle Foot Orthosis for Both Metal and Plastic KAFO Type' ASME 2013 International Mechanical Engineering Congress and Exposition IMECE2013, November 15-21, San Diego, California, USA, 2013.
- [34] Jumaa S. Chiad 'Study the impact behavior of the prosthetic lower limb lamination materials due to low velocity impactor' ASME 2014 12th Biennial Conference on Engineering Systems Design and Analysis, ESDA, 2014.
- [35] Muhsin J. Jweeg, A. A. Alhumandy, H. A. Hamzah 'Material Characterization and Stress Analysis of Openings in Syme's Prosthetics' International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS, Vol. 17, No. 04, 2017.
- [36] Zainab Yousif Hussien, Kadhim Kamil Resan 'Effects of Ultraviolet Radiation with and without Heat, on the Fatigue Behavior of Below-Knee Prosthetic Sockets' International Journal of Mechanical and Production Engineering Research and Development (IJMPERD), Vol. 07, No. 06, 2017.
- [37] Mohsin Abdullah Al-Shammari, Emad Q. Hussein, Ameer Alaa Oleiwi 'Material Characterization and Stress Analysis of a Through Knee Prosthesis Sockets' International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS, Vol. 17, No. 06, 2017.
- [38] Ayad M. Takhakh 'Manufacturing and Analysis of Partial Foot Prosthetic for The Pirogoff Amputation' International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS, Vol. 18, No. 03, pp. 62-68, 2018.
- [39] Jawad K. Oleiwi, Ahmed Namah Hadi 'Experimental and numerical investigation of lower limb prosthetic foot made from composite polymer blends' International Journal of Mechanical and Production Engineering Research and Development, Vol. 08, No. 02, pp. 1319-1330, 2018. <https://doi.org/10.24247/ijmperdapr2018151>.
- [40] Mahmud Rasheed Ismail, Muhannad Al-Waily, Ameer A. Kadhim 'Biomechanical Analysis and Gait Assessment for Normal and Braced Legs' International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS, Vol. 18, No. 03, 2018.
- [41] Muhsin J. Jweeg 'Application of finite element analysis to rotating fan impellers' Doctoral Thesis, Aston University, 1983.
- [42] Ayad M. Takhakh, Raied Z. Alfay, Abdul Rahim K. Abid Ali 'Effect of Ta addition on hardness and wear resist of Cu-Al-Ni shape memory alloy fabricated by powder metallurgy' BEIAC 2013-2013 IEEE Business Engineering and Industrial Applications Colloquium, 2013.
- [43] Muhannad Al-Waily, Maher A.R. Sadiq Al-Baghdadi, Rasha Hayder Al-Khayat 'Flow Velocity and Crack Angle Effect on Vibration and Flow Characterization for Pipe Induce Vibration' International Journal of Mechanical and Mechatronics Engineering IJMME-IJENS, Vol. 17, No. 05, pp.19-27, 2017.
- [44] Muhsin J. Jweeg, E. Q. Hussein, K. I. Mohammed 'Effects of Cracks on the Frequency Response of a Simply Supported Pipe Conveying Fluid' International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS, Vol. 17, 05, 2017.
- [45] Mohsin Abdullah Al-Shammari, Lutfi Y. Zedan, Akram M. Al-Shammari 'FE simulation of multi-stage cold forging process for metal shell of spark plug manufacturing' 1st International Scientific Conference of Engineering Sciences-3rd Scientific Conference of Engineering Science, ISCES 2018-Proceedings, 2018.
- [46] Rasha Hayder Al-Khayat, Maher A. R. Sadiq Al-Baghdadi, Ragad Aziz Neama, Muhannad Al-Waily 'Optimization CFD Study of Erosion in 3D Elbow During Transportation of Crude Oil Contaminated with Sand Particles, International Journal of Engineering & Technology, Vol. 07, No. 03, pp. 1420-1428, 2018. <https://doi.org/10.14419/ijet.v7i3.14180>.
- [47] Abeer R. Abbas, Kadhim A. Hebeaitir, Kadhim K. Resan 'Effect of CO2 Laser on Some Properties of Ni46Ti50CU4 Shape Memory Alloy' International Journal of Mechanical and Production Engineering Research and Development, Vol. 08, No. 02, pp. 451-460, 2018. <https://doi.org/10.24247/ijmperdapr201852>.
- [48] Ghaith G. Hameed, Muhsin J. Jweeg, Ali Hussein 'Springback and side wall curl of metal sheet in plain strain deep drawing' Research Journal of Applied Sciences, Vol. 04, No. 05, pp. 192-201, 2009.
- [49] Adnan S. Jabur, Jalal M. Jalil, Ayad M. Takhakh 'Experimental Investigation and Simulation of Al-Si Casting Microstructure Formation' Arabian Journal for Science and Engineering, Vol. 37, No. 03, pp. 777-792, 2012. <https://doi.org/10.1007/s13369-012-0189-2>.
- [50] Maier C. & Calafut T. 'Polypropylene – the definitive user's guide and databook' In: Woishnis, W. (Eds.), *Plastics Design Library* a Division of William Andrew Inc. New York; 1998.
- [51] Kadhim K. Resan, Abbas A. Alasadi, Muhannad Al-Waily, Muhsin J. Jweeg 'Influence of Temperature on Fatigue Life for Friction Stir Welding of Aluminum Alloy Materials, International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS, Vol. 18, No. 02, 2018.
- [52] R.A. Flinn and Trojan PK 'Engineering Materials and Their Application' 4th ed Bostan, Houghton Mifflin, 1990.