Development of Automatic Revolving Door

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***Abstract*—The existing manual revolving door was upgraded to an automatic revolving door for an aluminum company based in Jordan. The development process required a thorough dynamics and design analysis of the manual revolving door, and implementation and construction of an automatic control system responsible for regulating the rotational motion of the real automatic revolving door when the users pass through it. The automatic revolving door consists of the manual revolving door frame, control system, electric motor for powering the door, clutch that connects the motor with the pulleys which transmit the motion to the door, two sensors for detecting people motion, and a sensor for stopping the door in the right position. The door has the feature that it can be switched between automatic and manual operations which is good for maintenance purposes. In addition, in the case of electric blackout the door automatically switches to manual operation and thus does not stop the users from passing through it.**

***Index Terms*—Actuators, automatic control design, revolving door, sensors.**

I. Introduction

A revolving door as shown in Figs. 1 and 2 is a type of door that, as its name suggests, revolves in its frame. A revolving door, however, is set on a rotating shaft and has unlimited rotation. Around the shaft are several doors (called "wings" or "leaves") that are bolted to it and incapable of independent movement. The number of doors on the revolving door is three or four. The doors are powered via the central shaft. Revolving doors are usually used in hotels and restaurants, office and administration buildings service stations and banks.

There are two types of revolving doors: manual and automatic. The manual revolving door has push bars. When the push bar of the door facing the user is pushed, the entire assembly rotates. The other type of revolving doors is the automatic revolving door. It has a control system that is responsible for regulating the revolving door rotational motion based on desired specifications and without requiring the person passing through the door to push any bar. The control system consists of an automatic controller which is an analog/digital electric circuit, actuator which is the central shaft driving motor, sensors that detect the persons approaching the revolving door and the door angular position, and the revolving door itself which is the system to be controlled.

Revolving doors are transparent to allow users on either side of the door to see and anticipate each other to avoid being surprised by sudden operation. There is a pair of curved partial walls around the circumference of the revolving door with only openings sized to match an individual section of the revolving door. Thus, the revolving door prevents a direct path between the interior and exterior. In a sense, such a door is always closed, so wind and drafts cannot blow directly into the building. Revolving doors are favored because they can be used as a partial airlock to minimize building's heating and air conditioning losses. Some versions permit the individual doors of the assembly to be unlocked from the central shaft to permit free flowing traffic in both directions.

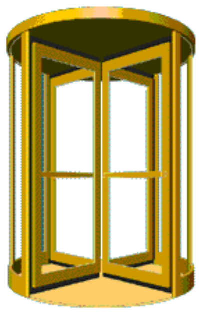

Fig. 1. 3D picture of the revolving door.

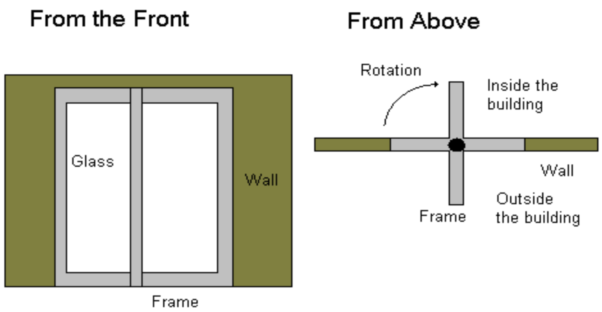

Fig. 2. The revolving door from front and above.

There is currently no company/factory in Jordan that manufactures automatic revolving doors. They are being exported from Europe and are very expensive. Kurdieh and Hakim Aluminum Company based in Jordan currently manufactures the manual revolving door. In this research the technology for manufacturing the automatic revolving door is made available to Kurdieh and Hakim Aluminum Company. Producing automatic revolving doors at this company will reduce cost, increase profits, enhance the products of the company, eliminate the need for exporting the automatic revolving doors from abroad, support industry and technology in Jordan, increase the number of available jobs locally and make maintenance easier, cheaper and faster.

Revolving door research is limited in the literature. Energy generation due to the rotational motion of the revolving door has been attempted recently in [1]. It was found that energy

Manuscript received July 9, 2018; revised August 28, 2018. This work was supported by the Jordanian national program Faculty For Factory (FFF) and Kurdieh and Hakim Aluminum Company based in Jordan.

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doi: 10.18178/ijmmm.2018.6.6.410

generation is optimum at certain rotational speeds that are around or exceed 13 RPM which is very fast. Comfortable revolving doors rotate a few revolutions per minutes. In [2], a control access revolving gate was modeled and constructed. The gate regulates people flow and counts passing persons. It is worthwhile to mention that the research of our paper gives the basic and main ideas for constructing an automatic revolving door control system.

The research presented here is a collaboration between academia and industry. University related projects are of great importance and are sometimes very beneficial to industry. Fresh minded people may have brilliant ideas that can be extended into excellent research topics and in some situations the ideas can be expanded to give valuable research results. In [3], a hybrid solar system project was extended into a research result. Furthermore, the topic was expanded to find the conditions for maximum efficiency of a solar integrated system [4]. This research led to adaptive prediction of the system [5] and simulation with adaptive neural networks [6]. Based on a university project at the Hashemite University in Jordan sun angle data were utilized to build a solar tracking panel and the results of this project in addition to using neural networks in the adaptive and non-adaptive modes came up with interesting research results [7]. At the German Jordanian university in Jordan a solar system was built and the setup led to results regarding its feasibility [8]. A university project that solved an industrial problem of load cell calibration was presented in [9]. The load cells were measuring the weight of grains in two silos and they had fault readings. Experiments were performed and a calibration formula for the load cells was proposed.

II. Dynamics and Mechanical Design

A thorough dynamics and design analysis of the existing manual revolving door is essential for the design of a good controller for the automatic revolving door. The driving torque will be considered as the input to the system whereas the rotational motion will be considered as the output of the system which we will eventually control. The door is a rigid body that rotates about a fixed axis which is the central axis. Applying the kinetic principles will produce the equations that describe the door's motion and relate the output and input of the system. These equations will then be used to select the drive motor which will actuate the door. Computer simulation will be performed and the results will be compared with the data obtained from the real door in order to verify the accuracy of the mathematical model.

The actuating or driving motor is selected such that it has enough power to revolve the door at desired speeds. The choice of motor depends on the interface mechanism between the motor's drive shaft and the central shaft of the door. Another factor that should be taken into account is the controller circuit required to actuate the motor. The major types of motors that could be used are DC and AC motors. The DC motor rotational speed is controlled via changing the input voltage and this kind of motor is powerful for speed control but its controller circuit is complicated. The AC motor will be another possible option and its controller circuit is simpler.

Drawings of the revolving door which will be upgraded to an automatic revolving door are shown in Fig. 3. These drawings provide the dimensions of the door. The materials composing the door are also essential to know for the dynamics and design analysis. The revolving part of the door is composed of glass, aluminum, latte wood and steel. The two important quantities to calculate are the mass and moment of inertia of the door. Matlab files were written to make such calculations and the results are: mass, m = 336 kg and moment of inertia, I = 222 kg.m^2.

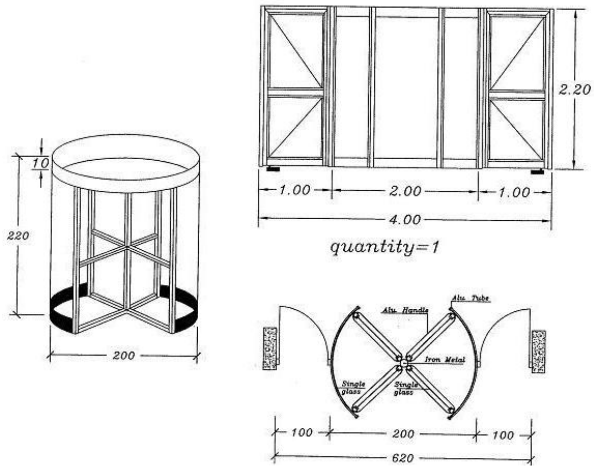

Fig. 3. Revolving door drawings.

An important quantity to determine is friction opposing the door rotational motion. Friction is taken into account in the dynamics analysis. It is very difficult to calculate friction analytically. Therefore, we have to conduct an experiment on the door and collect data which are then used to determine friction numerically. The required revolving door with the appropriate dimensions was not available at the time of experiment but a smaller version of the door was available. The mass of the smaller door is m_small = 117 kg and its moment of inertia is I_small = 13 kg. m^2. It has a height of 1.25 m and diameter of 1 m. We will determine the friction of the smaller door version experimentally and use dynamics analysis to convert this friction to the required larger door.

The following experiment was conducted: the door was given a push initially and the times at pre-specified angular positions were recorded. The data points are plotted in Fig. 4 along with the least squares curve fit. Fitting of the data gives the following relation of angular position θ (in degrees) as a function of time t (in seconds)

$$\theta = -22.67t^2 + 195.43t - 2.65 \tag{1}$$

Differentiating the above function twice we obtain the angular acceleration in the experiment. The angular acceleration is equal to -45.34 deg/s^2. Multiplying this value by π and dividing by 180^o we get the angular acceleration in rad/ s^2 which is equal to α = -0.79 rad/ s^2. The negative sign indicates that we have deceleration. The only force on the door in the experiment is the angular friction, F_f_small, which opposes the motion. Applying Newton's second law in the direction opposite to the door motion, we get

$$\sum M = (I\_\text{small})\alpha \tag{2}$$

$$F_{f\_small} = (13)(0.79) = 10.28 \text{ N.m} \quad (3)$$

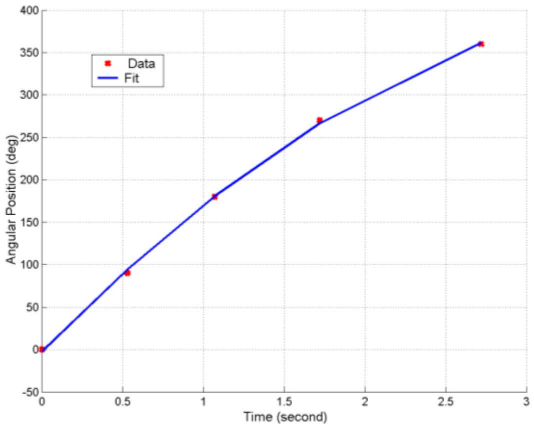

Fig. 4. Curve fitting of the friction experimental data.

It is well known that the friction force is equal to a factor (called the friction coefficient) times the normal force on the surface of contact. We assume that the friction coefficients for the small and large (under consideration) doors are the same since they have equivalent designs but different dimensions. Therefore, the friction force is linearly proportional to the weight of the door and it can be calculated for the large door as follows

$$F_f = \frac{m}{m_{small}} * F_{f\_small} = \frac{336}{117} * 10.28 = 29.45 \text{ N.m} \quad (4)$$

We will need an electric motor to drive the revolving door in the automatic mode. The torque delivered to the door must be greater than the friction force. Note that the calculated friction force is the kinematic one. The motor should actually overcome the static friction which occurs just before the motion starts. In order to estimate the static friction a string is extended from one of the door push bars to a known hanging mass. The string is located at the farthest point from the door center. The distance between this point and the center is equal to the door radius which is 0.5 m. We tried a 2 kg mass and a 4 kg mass for the hanging mass. The 2 kg mass was not able to move the door. On the hand, the 4 kg mass rotated the door from rest with ease. The moment of the 4 kg mass is equal to the weight times the radius of the door, that is, (4*9.81)*0.5 = 19.62 N.m. The static friction will be less than this value. However, assuming that the static friction is equal to 19.62 N.m gives a factor of safety. Using the same reasoning as above, the static friction for the large door can be found as

$$F_{fs} = \frac{m}{m_{small}} * F_{fs\_small} = \frac{336}{117} * 19.62 = 56.34 \text{ N.m} \quad (5)$$

Therefore, the torque delivered to the door should be greater than this static friction value.

Another important quantity to determine is the rotational speed of the door which is comfortable for the persons passing through the door. Standards include an appendix containing many drawings and charts to help explain the standard's provisions. Included in the provisions is maximum door RPM that varies with door size and kinetic energy limits. The RPM of the doors is based on the walk speed of a person passing at the outer end of the wing. Automatic doors are based on a walk speed of 3 feet per second and the manual door is a little faster at 4 feet per seconds (which is currently in the model building code charts). Many standards include limits of kinetic energy allowed when the door comes in contact with a person. For example, the ANSI A156.10 standard is based on a maximum of 2.5 foot pounds of kinetic energy. This limit has been in the UL 325 standard for pedestrian doors for years (UL 325 is the Underwriters Laboratories standard that manufacturers must meet to get their products listed). The writers of the revolving door standards followed that guideline and developed a formula to calculate the maximum RPM at a point of contact with a person. Wing sensors can be used to slow the door from its normal run speed (RPM) to the maximum kinetic energy provision. Weight and speed of travel are two main elements of the kinetic energy formula. Manufacturers will provide a chart with their installation instructions to tell the person setting the door speed or doing the inspection what the maximum kinetic energy speed can be (manufacturers will likely provide the information as RPM rate so that it can be measured in the field).

Based on the above discussion we will compute the rotational speed of the automatic revolving door that we are going to design. The radius of the door is 1.25 m which is the same as the distance from the door center to the outer end of the wing. Note that this radius is larger than the 1 m given in Fig. 3. The whole design was based on the 1.25 m radius as the requirement of Kurdieh and Hakim Aluminum Company. The speed at the outer end following the above standards is equal to 3 ft/s = 0.91 m/s. The rotational speed is given as the speed at the outer end divided by the door radius, that is

$$\omega = \frac{V}{r} = \frac{0.91}{1.25} = 0.73 \text{ rad/s} \quad (6)$$

$$\omega = 0.73 * \frac{60}{2\pi} = 7 \text{ RPM} \quad (7)$$

We conclude from the above discussion about friction and speed that the drive motor should have at least a torque T of 56.34 N.m (safe value of static friction) and a rotational speed of 7 RPM. The minimum output power of the motor can be calculated as

$$\min P = T \times \omega = 56.34 \times 0.73 = 41.13 \text{ Watt} \quad (8)$$

It might be difficult to find a motor with a rotational speed of 7 RPM. The important quantity that must be satisfied is the minimum power of 41.13 Watt. If the motor speed is different from 7 RPM, a 7 RPM speed can be delivered to the door by using a transmission system such as a pulley, chain or gear system. Note that when a transmission system is used the power is preserved. This means that the torque times rotational speed stays constant. We searched the market in Amman-Jordan for the best appropriate electric motor for our automatic revolving door application and the motor selection is described in the next section.

III. Control Design and Performance

A control system that upgrades the manual revolving door to an automatic revolving door will be designed and implemented. The control system is responsible for the door motion as people approach and exit the door. The feedback loop of the control system is shown in Fig. 5 and it consists of the following main components: an automatic controller which is an electronic circuit, actuator which is the central shaft driving motor, sensors that detect the persons approaching the revolving door and the door angular position, and the revolving door itself which is the system to be controlled.

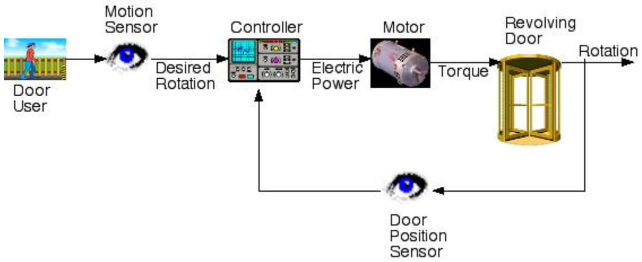

Fig. 5. The automatic revolving door control system.

The actuating or driving motor is selected such that it has enough power to revolve the door at desired speeds. The choice of motor and the interface mechanism (transmission system) between the motor's drive shaft and the central shaft of the door is based on the dynamics and the design analysis provided in the previous section. Another factor that should be taken into account is the controller circuit required to actuate the motor. The major types of motors that could be used are DC and AC motors. The DC motor rotational speed is controlled via changing the input voltage and this kind of motor is powerful for speed control but its controller circuit is complicated. The AC motor will be another possible option and its controller circuit is simpler.

Three sensors will be needed for the automatic operation of the revolving door. Two sensors are motion detectors that give signals when users approach the door from either side. The third sensor detects the angular position of the door and provides the controller with the information needed to stop the door at the correct position after users pass. There are various types of available sensors that can achieve these tasks. The appropriate sensors will be selected taking into consideration availability, cost, controller circuit and performance.

Based on the dynamics and design analysis and choice of motor and sensors, a control strategy for the revolving door will be designed and investigated. We can think of the controller as the interface between the sensors and the actuator or driving motor. It must be able to take the sensors signals as inputs and provide the appropriate electric power to the driving motor in such a way the objectives of door operation are satisfied. The basic idea of the controller is to power (on signal) the motor when a user approaches the door from either side. A timer will hold the on signal to the motor for enough period of time. This time is set based on practical experience and existing standards. Different possible controller circuits were investigated and the best one was selected. The designed controller provides the revolving door with very smooth and desirable motion.

An important feature that the revolving door must have is that we should be able to choose automatic or manual operation mode through an electric switch. This feature enables the door control system maintenance without preventing people from passing through. In addition, in the case of electric blackout the door must automatically switch to manual mode and thus does not stop the users from passing through it. Different electric and mechanical solutions were investigated. It was found that the best way to provide the door with the above features is to use an electric clutch between the motor shaft and the transmission mechanism of the door.

We searched the market well for the driving electric motor, transmission mechanism, electric clutch, sensors and controller components. During the search cost, quality, performance, connection and consistency between various parts were kept in mind. After tedious work we found and bought all the parts required for the control system of the automatic revolving door. The description, function and specifications of each part are described below

1) Electric motor: is the actuator that delivers power to the revolving door. This is an AC motor with output power of 60 Watt and speed of 17.5 RPM. Recall that the minimum power required for the automatic revolving door is 41.13 Watt as found in the dynamics and design analysis section. In the same section we calculated the rotational speed of the door as 7 RPM. Therefore, we will need a transmission system that reduces the speed of the motor from 17.5 RPM to 7 RPM at the door's central shaft. We will describe the transmission system shortly.
2) Electric Clutch: It connects the motor to the transmission system when it is supplied by an electrical signal and in this case we have automatic mode. When the electric signal is off the motor shaft rotates freely and there is no power delivered to the revolving door. In the latter case the door is in the manual mode. Thus, the clutch is the main part for switching between automatic and manual modes. There is an electric switch for the overall automatic door system. The on state of the switch provides automatic operation whereas the off state of the switch provides manual operation. In addition, in the case of electric blackout there is no power supplied to the clutch which means that the door mode will automatically switch to manual. The clutch operating voltage is 24 volts. We bought a transformer that converts the AC supply of 220 Volts to a DC voltage of 24 Volts. The transformer supplies the clutch with power through a diode.
3) Transmission system: transfers the power from the motor to the revolving door at the required speed. The transmission system can be a pulley, chain or gear system. We investigated all of these possibilities and concluded that the best transmission system is the pulley one. It is very suitable, safe, almost noiseless, cheap and available in the market. The pulley system consists of two pulleys and a belt. The motor speed is 17.5 RPM and the door should revolve at 7 RPM. Thus the motor speed should be reduced by 2.5 times. The diameters of the two pulleys diameters should have also a ratio of 2.5:1 in order for the door to revolve at 7 RPM. The small pulley rotates with the motor shaft and has a diameter of 7.5 cm. The big pulley revolves with the central shat of the door and has a

diameter of 19.07 cm. A belt that connects the two pulleys is 13 mm wide with a 120 cm perimeter. The electric motor, electric clutch and small pulley are assembled. The clutch connects the motor with the small pulley and thus transfers power from the motor to the transmission system when it is supplied with electric power. The shaft of the motor is fitted into a circular hole on one end of the clutch. The other end of the clutch is a shaft on which the small pulley fits. The motor shaft had a diameter of 12 mm whereas the diameter of the clutch circular hole is 11 mm. We had to machine mill the shaft of the motor to an 11 mm diameter before assembling it to the clutch.

4) Infrared motion sensor: detects the motion of persons approaching the door and sends a signal to the controller in order to provide the door with the appropriate rotation. Two infrared sensors are used for the automatic revolving door. They are mounted on the ceiling at the two opposite entrances of the door. The infrared motion sensor that we obtained is PIR model: MB–022. It has the following main properties

   a) Saving energy.
   b) Security purpose.
   c) Comfort.

5) Proximity switch: is an electrical switch that changes its status from off to on when objects are come very close to its detecting surface. The proximity switch acts as a sensor for the door's angular position. It is responsible for sending the stopping location information to the controller which stops the door at the correct position with entrances wide open. Our proximity switch is MAXTECH model: KC-3425-A1. Its operating voltage is 110 – 220 V and current is 200 mA. It is installed on the ceiling at the same angular position of the end of the partial circular fixed walls. When one of the four leaves comes to the same angular position the proximity switch turns on.

6) 6) Controller: takes the signals from the sensors and provides the power to the electric motor. The controller can be thought of as the interface between the sensors and actuator (motor). It consists of two relays and a timer. The relays are SCHRACK model: RN 306220. The relay coil is 220 VAC. The timer is built in with the infrared motion sensor. Its delay time can be set between 5 and 480 seconds. Based on the door requirements and standards we set the time to 15 seconds. This means that after the user is detected by the infrared motion sensor it will keep the signal for 15 seconds.

The ladder diagram that represents the automatic revolving door control system is shown in Fig. 6. The two infrared motion sensors are connected in parallel to the coil of the first relay M_1. The proximity switch is connected to the coil of the second relay M_2. The two relays are connected in parallel to the motor and M_1 is normally open whereas M_2 is normally closed. The door will stop only if the two relays are switched off. This happens if the coil of M_1 is not activated and the coil of M_2 is activated. When a user approaches the door from either side, the coil M_1 is activated by the infrared motion sensor for 15 seconds and hence passes electric power to the motor which revolves the door through the pulley system. After the 15 second period passes the relay M_1 switches off, but the door will not stop until the proximity switch activates the coil of relay M_2 to switch the motor off. The proximity switch will activate the coil of M_2 when the door comes to the final correct position (when one the four leaves comes to the same angular position of the proximity switch). Since the revolving door has four leaves it will revolve for a maximum of one quarter of a revolution after the 15 seconds pass and before it comes to a complete stop.

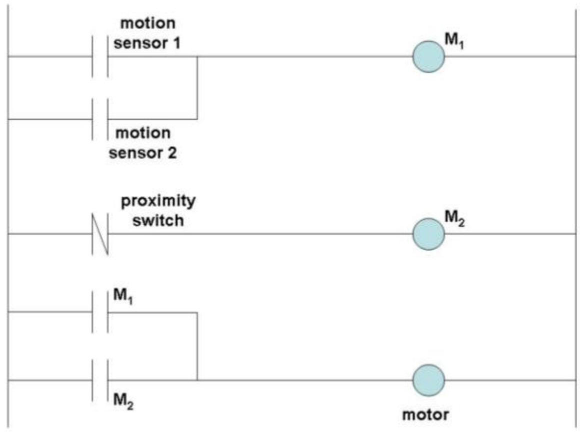

Fig. 6. Ladder diagram for the automatic revolving door control system.

IV. Conclusion

A control system for the revolving was developed for an aluminum company based in Jordan. The company was provided with the technology to manufacture automatic revolving doors and upgrade their existing manual revolving door. This will potentially enhance the company products, increase the company profits, reduce the automatic door cost, eliminate the need for exporting the automatic revolving doors from abroad, support industry and technology in Jordan, increase the number of available jobs locally, support the idea of academia/industry collaboration and make maintenance easier, faster and cheaper. The door can be used in hotels and restaurants, office and administration buildings, service stations and banks.

The automatic revolving door control system was designed and implemented. It consists of two infrared motion sensors, one proximity switch, two relays, electric motor, electric clutch, pulleys and belt. The door performs well similar to those doors exported and it follows the international standards. When a person approaches the door from either side it revolves for about 15 seconds and then stops at the right position ready for new users. The door has the feature that it can be switched between automatic and manual operations which is good for maintenance purposes. In addition, in the case of electric blackout the door automatically switches to manual operation and thus does not stop the users from passing through it.

The developed automatic revolving door can be improved in the future after it is used in practice and people feedback is obtained. Furthermore, advanced options can be added to the door that provide comfort and additional safety features. The door start and stop processes can be made gradual which provides more comfort for people passing through the door. Appropriate sensors can be installed and the control system can be accordingly adjusted to safely stop the moving door when it touches a passing person. Last but not least, wing sensors can be used to slow the door from its normal run speed to a safe speed for slow passing persons.

ACKNOWLEDGMENT

We would like to thank the Jordanian national program Faculty For Factory (FFF) for giving us the opportunity to collaborate with industry and produce a state of the art product. We also would like to thank Kurdieh and Hakim Aluminum Company based in Jordan for giving us the support and available information for the project.

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