New Electronic Peening Intensity Sensor: Theory and Experimental Validation

Sylvain A. Forgues[1], Brigitte Labelle[1], Ramzi Ben Moussa[1], Adel Alouani[1]

[1] Shockform Aeronautique Inc., Canada, engineering@shockform.com

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Abstract

The method to measure peening intensity has not evolved significantly in decades. The current method is time intensive as it requires peening of several metal strips to different times in order to generate a saturation curve. Each strip must be pre-measured, installed on a holder, peened for a specific amount of time, removed from the holder, measured once more and the value recorded manually. These recorded values must then be made into a graph and the intensity calculated using what is called the “10% rule”. All these steps to find intensity make peening a complicated process that is confusing for many operators.

A recently developed wireless sensor offers the possibility to simplify intensity calculations with real-time process measurement and continuous transfer and analysis of data. This sensor is part of a new trend known as the Internet of Things (IoT) and promises to allow companies to progress into the latest industrial revolution called Industry 4.0.

Objectives

The objective of the paper is to introduce the theory and experimental validation behind this new electronic peening intensity sensor. The concept of impact force will be presented and discussed as an alternative to Almen intensity for peening

Sensor Description

The sensor’s characteristics and properties are first presented to provide a good understanding of its functions and capabilities. The sensors’ exterior is illustrated in Figure 1. It features a load cell pin, a protective cover, a metal base with an on/off button and five screw locations for permanent installation.

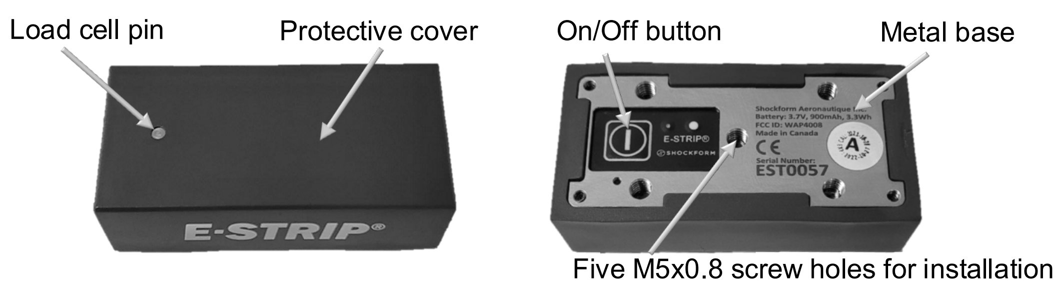

Figure 1 Sensor Features

The sensor has the size and screw pattern of an SAE J442 [1] Almen strip holder. This allows for easy installation on most jigs and fixtures currently used for peening intensity determination and verification. The load cell pin is made of tungsten carbide for durability and receives the impacts from the peening media. The sensor has a protective cover that absorbs the impact energy of the media and protects the internal components of the device. This protective cover can be replaced if necessary but has shown little wear from all the testing performed so far.

Each impact on the load cell is recorded and sorted and only a few hundred impacts are necessary to determine the intensity. Once the peening is completed, an equivalent intensity is calculated by the sensor using a proprietary algorithm. The equivalent intensity and the number of impacts are sent wirelessly to a computer where it is displayed in the form of a histogram (Figure 2). The sensor offers a huge time saving since no human interaction is required to load, unload and measure Almen strips to determine or verify intensity.

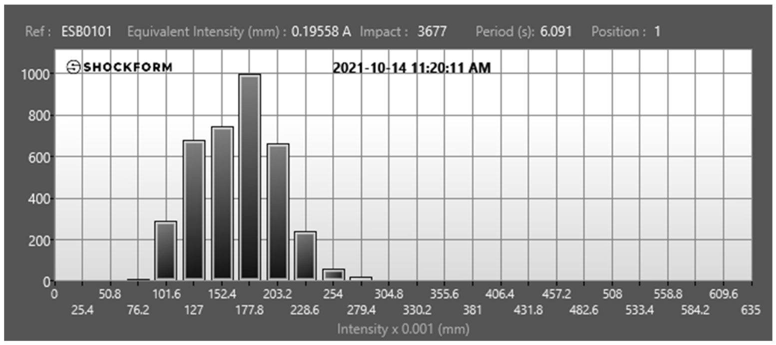

Figure 2 Sensor Output Histogram with equivalent intensity and number of impacts

Theory

The theoretical equations governing the utilisation of the sensor is found in most basic physics handbooks [2]. It is repeated here for completeness.

Consider a peening particle of mass m moving in a xy plane at speed $\vec{v}$ and acted on by a force $\vec{F}$ during a period of time t. From Newton's second law, the force acting on the particle can be defined as follows:

$$\vec{F} = m\frac{d\vec{v}}{dt} \tag{1}$$

By rearranging, we get

$$\int_{t1}^{t2} \vec{F}dt = \int_{v1}^{v2} m\, d\vec{v} \tag{2}$$

The Impulse–Momentum principle is derived from equation (2) with impulse on the left and change of momentum on the right of the equation. It states that the Impulse defined as the force acting on a particle over a period of time is equal to the change in momentum of the particle defined as the mass multiplied by the change in velocity of the particle.

In our application, the peening particle is hitting the load cell pin. The particle has a velocity v_{in} toward the sensor just before the impact and a velocity v_{out} away from the sensor just after the impact. We select v_{in} with a negative sign and v_{out} with a positive sign since they are in opposite directions. Since the mass of the particle is assumed constant during the impact, the above equation then becomes:

$$\int_{t1}^{t2} \vec{F}dt = m\,(v_{out} - (-v_{in})) \tag{3}$$

or

$$\int_{t1}^{t2} \vec{F}dt = m\,(v_{out} + v_{in}) \tag{4}$$

A relation exists between v_{in} and v_{out} known as the coefficient of restitution.

$$C_R = \frac{v_{out}}{v_{in}} \quad (5)$$

The coefficient of restitution is defined as the ratio of the velocity after impact to the velocity before impact. Coefficients of restitution depend on factors including material properties, body geometry, and impact velocity. During peening some kinetic energy is dissipated during the impact and $0 < C_R < 1$.

Equation (4) can be re-written as

$$\int_{t1}^{t2} \vec{F} dt = m\,(C_R + 1)\, v_{in} \quad (6)$$

From testing, and from the literature [3-4], we also know that there is a direct relationship between shot velocity before impact and peening intensity.

$$v_{in} = K_B\ I_A \quad (7)$$

where I_A is the Almen intensity and K_B is a factor associated with particle properties.

Replacing equation (7) in equation (6) gives us a direct relation between the impulse and the peening intensity:

$$\int_{t1}^{t2} \vec{F} dt = m\,(C_R + 1)\, K_B\ I_A \quad (8)$$

where the mass m, the coefficient of restitution C_R and the factor K_B are properties of the peening particle involved in the impact of the peening process.

The integral on the left side of equation (8) can be evaluated when the force applied on the particle is known as a function of time. During impact, this interaction can be simplified as illustrated in Figure 3. As the particle hits the sensor, the force gradually increases as the velocity decreases until the force reaches a maximum value F_{max}. The force then gradually decreases as the particle departs in the other direction until the force reaches zero.

The area under the curve in Figure 3 is equal to the impulse of the impact. In this case, it can be calculated as the area of a triangle with:

$$F\Delta t = A = \frac{1}{2}(base)(height) \quad (9)$$

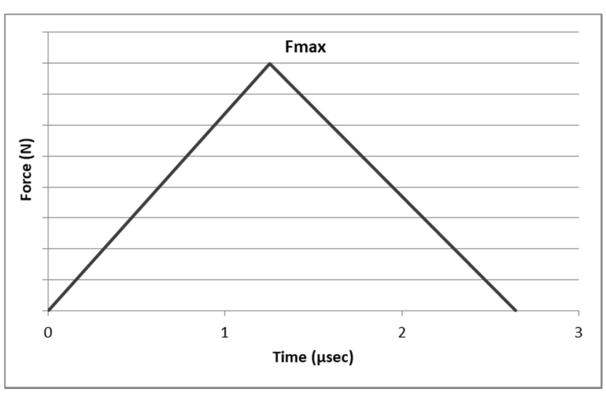

Figure 3 Graphical illustration of particle force of impact over time

Where the base of triangle is the duration of the impact and the height of the triangle is the maximum force of impact F_{max}. Equation (9) then becomes:

$$F\Delta t = A = \frac{1}{2}\left(t_{impact}\right)\left(F_{max}\right) \tag{10}$$

Merging equations (10) and (6) we get a relationship between the maximum impact force and the velocity before impact.

$$\frac{1}{2}\left(t_{impact}\right)\left(F_{max}\right) = m\,(C_R + 1)\,v_{in} \tag{11}$$

Rearranging, the maximum impact force can be calculated as follows:

$$F_{max} = \frac{2\,m\,(C_R + 1)\,v_{in}}{t_{impact}} \tag{12}$$

The max force F_{max} can be calculated since the mass m, the coefficient of restitution C_R , the initial velocity v_{in} and the time of impact t_{impact} can be measured. Merging equation (12) and (7), we see that F_{max} has a direct relationship with Almen Intensity I_A.

$$F_{max} = \frac{2\,m\,(C_R + 1)\,K_B\,I_A}{t_{impact}} \tag{13}$$

For our sensor, we believe the impulse is measured directly by the load cell. This will be confirmed if a linear relationship exists between the sensor output and Almen intensity. We also believe the Almen intensity can be represented very simply by the maximum impact force. Both of these concepts will be illustrated in the experimental validation.

Experimental Validation and Discussion

The experimental validation is performed with ACWR28 media meeting specification AMS2431/3 [5]. The average mass of one particle of media was determined by weighing 2000 particles. The average mass of one particle was found to be 1.85E-06 kg. This is within the 1.80E-06 to 2.50E-06 kg range specified in the specification.

A special apparatus was developed to calibrate the sensor. This apparatus shoots one or multiple particles at the sensor while measuring the velocity v_{in} of the particles just before impact. Since the sensor allows the measurement and recording of each impact, it is possible to see the change in output of the sensor over a period of time as illustrated in Figure 4. The area under the curve represents the impulse of the impact where the maximum value of the sensor is F_{max} and the impulse time is t_{impact} as per equation (10).

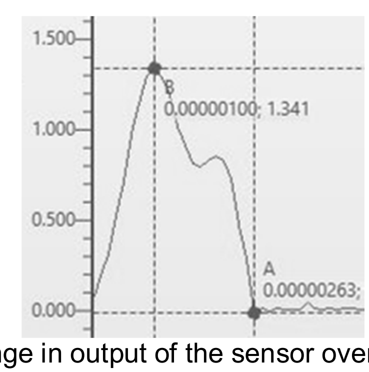

Figure 4 Change in output of the sensor over a period of time

The apparatus also allows the peening of Almen strips for the same set of initial velocities. It is then possible to plot sensor output in function of Almen intensity as illustrated by Figure 5. The graph confirms the linear relationship between the sensor output representing the impulse of the impact and the peening intensity as expressed in equation (8).

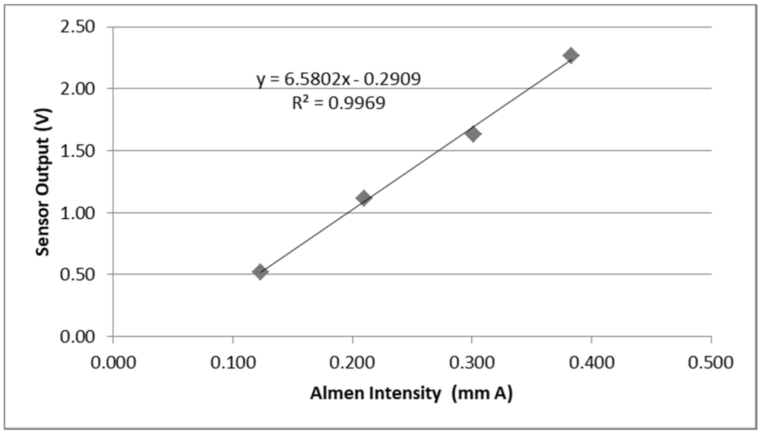

Figure 5 Sensor Output vs. Almen Intensity

Particle velocity before and after impact was determined using another apparatus developed internally and inspired from the work in Reference [6]. This apparatus uses a camera, LED lighting and an image analysis software to measure the velocity of the particle before and after impact with the sensor pin. A typical image is shown in Figure 6 where the velocity before impact is expressed in meters per second. The image for the velocity after impact is analysed separately.

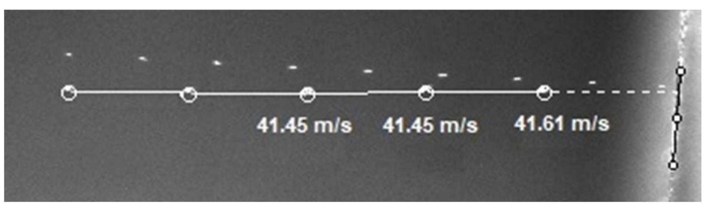

Figure 6 Measurement of particle velocity before impact on sensor

Knowing the particle mass, the velocity before impact, the coefficient of restitution and the impulse time taken from the sensor, it is possible to calculate the maximum force of impact F_{max} using equation (12). Calculations are presented in Table 1.

Table 1 Average data for ten measurements taken at four different initial velocities

Initial Speed Vin (m/s)	Final Speed Vout (m/s)	Coefficient Restitution	Sensor Max Output (V)	Calculated Fmax (N)	Intensity (mm A)
13.4	7.7	0.57	0.522	30.2	0.124
25.4	12.6	0.50	1.115	54.4	0.209
39.4	16.9	0.43	1.632	80.7	0.301
52.8	20.7	0.39	2.264	105.2	0.384

The coefficient of restitution changes with initial velocity since more energy is lost for impacts at higher velocities than at lower velocities [7]. However, the time of impact does not change with velocity. It is believed to be a function of particle material and size. For AWCR28 media, the average time of impact on the sensor was found to be 2.59E-06 seconds.

The data in the table shows that a particle of AWCR28 produces an impact force of 30 N for a peening intensity of 0.124 mmA. That force increases to 105 N for a peening intensity of 0.384 mmA. The relation between F_{max} and Almen intensity is shown in Figure 7.

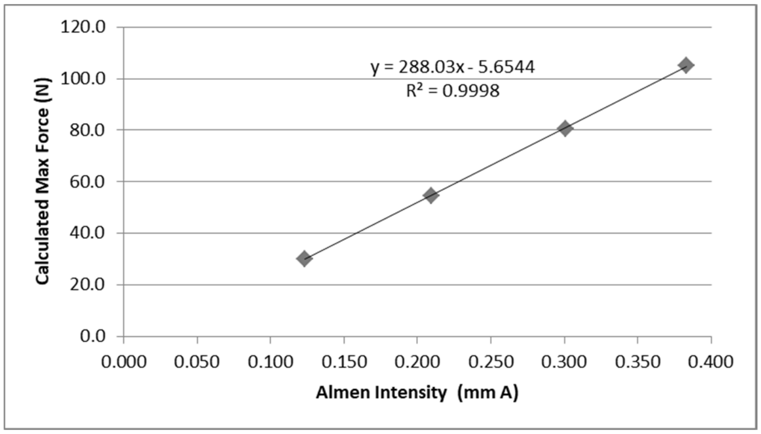

Figure 7 Calculated Fmax vs. Almen Intensity

The graph shows a nearly perfect linear relationship. Using the maximum impact force to define peening intensity would greatly facilitate the understanding of the process. The maximum impact force can be illustrated by a hammer hitting a surface. A higher impact force will generate a deeper level of compressive stress. This is much simpler to understand than the relation between arc height of a metal strip and Almen intensity. Especially since the peening time on the metal strip is important when generating the saturation curve. This leads to much confusion for many people in the industry.

Conclusion

A new electronic peening intensity sensor is presented in this paper. The sensor development and usage are backed by fundamental physics equations and illustrated by experimental data. The data shows that the output of the sensor correlates very well with Almen intensity. The sensors could therefore be a good alternative to Almen strips. The sensor output can provide a measure of maximum impact force which was also shown to have a nearly perfect linear relationship with Almen intensity. The use of maximum impact force to quantify the peening intensity offers the possibility to greatly facilitate and improve the understanding of the peening process. Testing of the force-intensity relationship for other types, size and hardness of media is under way and will be presented in future technical papers.

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