Non-Destructive X-ray Evaluation and Gap Measurement of Ceramic Armor Plate

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Abstract. Ceramic armors are usually made of a close-fitting periodic array of ceramic tiles, and have gaps between the tiles. The ballistic performance of the ceramic armor is highly affected by the gap width and it is important to find a way to inspect and evaluate it with no destruction. So the gaps of two ceramic armor plates, which were respectively made through hot-press vulcanization machine and autoclave system, were inspected and measured by a non-destructive X-ray evaluation method. But because of the magnification effect of the X-ray method, the measured gap width was not real. So that, it is critical to find the relation between the actual gap width with the measured. Though analysis of the magnification effect of X-ray inspection, we proposed a formula between the two, and calculated the actual gap width of the two different armor plates. It could be concluded that the autoclave method was better, with mean gap width was only 34% of that hot-press vulcanization machine made.

1. Introduction

Weight reduction is the highly demand for the military armored vehicles and the composite ceramic add-on armor is the most effective mean of lowering armor weight while maintaining the protection level. The composite vehicle armor system usually consist of several different type materials, and commonly is composed of ceramic plate, metal plate and fiber reinforced laminate. It mainly depends on the ceramic to fracture and erosion the coming projectile. But because of its fragility the ceramic itself will also be damaged during the interaction with the projectile[1-3]. So that ceramic-based armor is commonly made up of a periodic array of many tiles. This structure can minimize the damage into one ceramic tile and ensure the multiple hit capability. Jiusti et al.[4] showed the importance of gap filling materials to prevent tile-to-tile contact. Adhesive material, which infiltrates the inter tile gaps, acts like a frame, which maintains the confinement of fractured tiles and prevents the spreading of cracks. Anderson et al.[5] reported that the dependency of the ballistic performance of ceramic tiles is sensitive on the confinement. But owing to the edge effect of the ceramic, inter tile gaps are points of higher vulnerability of tiled armor systems. W Seifert et al.[6] studied the impact position’s affection of the ballistic performance of tiled adhesively bonded ceramic/metal targets and concluded that the ballistic resistance decreased significantly with increasing gap width. So that accurate manufacturing control of the gaps, as well as reliable post-manufacturing gap inspection, is necessary.

The inter tile gaps is influenced by the accuracy of the tile dimensions, the flatness of the tile edges, the accuracy of the tile arrangement process, the temperature of vulcanization and the way of pressing. The mainly purpose of this study is to select the better fabrication method from the hot-press vulcanization and autoclave.
This work quantitative assessed the width of two different ceramic armor plates using post-manufacture X-ray method. Because of the confinement layer of ceramic armor plate is opaque and the tile array layer is located in the armor interior where direct visual inspection and measurement is not possible, X-ray is the only practical non-destructive evaluation method available to make quantitative width measurements of the gaps[7].

Due to the magnification effect of the X-ray method, the measured gap width is not real. So we analyse the X-ray detection process and found the amplification distortion’s reason. After this work, we proposed an equation to calculate the actual gap width and assessed the gap width of two different armor plate.

2. Experiment Process

2.1. Fabrication of Ceramic armor plate
Two ceramic armor plates was manufactured respectively through hot-press vulcanization machine and autoclave system. The pressure of vulcanization machine is generated by the hydraulic cylinder, and the temperature is provided by the heat transfer oil. The pressure of autoclave system is generated by the hot compressed gas in the autoclave system.

The ceramic armor plates were composed of hexagon ceramic tiles, glass fiber cloth, carbon fiber cloth and thermoplastic resin.

2.2. X-Ray detection Equipment and Imaging
The X-Ray detection Equipment arrangement is showed in Figure 1, which is composed of the X-ray source, Aperture, movable table, digital screen and control system. The control system can control the table’s translation and capture the digital image from the digital screen. The ceramic armor plate is settled on the movable table. And according the tested plate dimension, we can capture several X-ray digital images through the software in the control system.

To ensure coverage of every gap, multiple overlapping X-ray picture were taken with each array, which was routinely done through the translation of the movable table. These X-ray pictures were combined to form digital composite image of the entire tile arrays. The X-ray images of the ceramic armor plates manufactured through press vulcanization machine and autoclave system are illustrated in Figure 2.

![Figure 1. X-ray detection arrangement](image-url)
2.3. Identification of Gaps
As illustrated in Figure 2, to organize the Gaps for study, they were numbered according its location. The horizontal gaps were numbered with H*, and the upper vertical gaps were numbered with VU*, and the last lower vertical gaps were numbered with VD*.

3. Measurement of Digital X-ray Film Images
Due to the magnification effect of the X-ray method, we firstly analysesed the X-ray detection process. The center of the digital X-ray image, the intersection point of the red diagonal line of the picture, corresponds the center of the X-ray source aperture. Because of the conical shape of X-ray and the 3-dimensional of the ceramic tile gap, the gap width measured from the digital image is greater than actual. So, in order to assess the gap width of the two different armor plates, we must find the relationship between the measured with the actual width.

The amplification come from two sources, which one is the conical shape of the X-ray and the other is the thickness of the ceramic tile.
Figure 3. The amplification from the conical X-ray

As we can see from Figure 3, because of the conical shape of the X-ray, the measured gap width is slightly bigger than the actual. The amplification ratio can calculated from the following Equation (1).

\[
\frac{W_a}{W_m} = \frac{H}{H+L} = 0.94
\]  

Where \(W_a\) is the actual gap width; \(W_m\) is the measured gap width; \(H\) is the height of the X-ray aperture from table; \(L\) is the distance between the table and the digital screen.

Figure 4. The amplification from X-ray tile side penetration

The other source is the side view penetration of the X-ray. As illustrated in the Figure 4, the incoming angle \(\alpha\) is related with the height of the X-ray Aperture and the distance of the gaps position from radical center. So the angle \(\alpha\) can be calculated from the following equation,

\[
\alpha = \tan^{-1} \left( \frac{H}{S} \right)
\]  

(2)
Where $\alpha$ is the incoming angle of the X-ray and $S$ is the distance of the gap position from radical center.

As showed in Figure 4, when the X-ray incoming with an angle $\alpha$, the gap on the image is divided into two parts. The one is the green area, which is equal with the actual gap width, and the other is caused by the X-ray incoming from the side view of ceramic tile ($W_p$), which is equal with the ceramic thickness multiple with the incoming angle. When the actual gap width $W_a$ is less than the projection width $W_p$, the gap on the digital image is grey. And when the $W_a$ is larger than the projection width $W_p$, the gap on the digital image is white with grey blurred area.

As we can see from Figure 5, the following Equation (3) is proper in two situations:

$$W_a = W_m - T \times CTan(\alpha)$$

Where $T$ is the thickness of ceramic tile.

![Figure 5](image)

**Figure 5.** The relation between the width with X-ray incoming angle

Because the actual ceramic tile is hexagonal, different edge has a different angle with the incoming X-ray. So the formula must take this angle account. We can calculate the width through the following equation,

$$W_a = W_m \times \sin \beta$$

Where $\beta$ is the angle between incoming X-ray direction and the tile edge. The angle $\beta$, can be easily calculated through the following equation,

$$\beta = |\beta_x - \beta_c|$$

Where $\beta_x$ is the angle between incoming X-ray direction and horizontal line; $\beta_c$ is the angle between tile edge and horizontal line.

Take all these factors above account, we can conclude the relationship between actual and measured gap width as following equation,

$$W_a = (W_m - T \times \frac{S}{H}) \times \sin|\beta_x - \beta_c| \times \frac{H}{H+L}$$

4. Results and Discussion

The gap widths were measured through the Adobe Photoshop software and then the actual gap widths were calculated through the formula proposed. The results with two different plates is summarized in Table 1. The mean gap width with autoclave method is only 34% of hot-press vulcanization machine made, and the max width is 50%.
Table 1. The gap widths of two different armor plate

| Process                   | Autoclave | Hot-press |
|---------------------------|-----------|-----------|
| Ceramic thickness $T$ (mm)| 16        | 16        |
| Horizontal Edges $H^*$    |           |           |
| Mean                      | 0.163     | 0.559     |
| Max                       | 0.662     | 1.173     |
| Min                       | 0         | 0.066     |
| Std                       | 0.171     | 0.297     |
| Mean                      | 0.224     | 0.487     |
| lower vertical gaps $VD^*$|           |           |
| Max                       | 0.800     | 0.970     |
| Min                       | 0         | 0.024     |
| Std                       | 0.225     | 0.220     |
| Mean                      | 0.135     | 0.485     |
| upper vertical gaps $VU^*$|           |           |
| Max                       | 0.522     | 1.542     |
| Min                       | 0         | 0.018     |
| Std                       | 0.157     | 0.304     |
| Mean                      | 0.174     | 0.513     |
| All the Edges             |           |           |
| Max                       | 0.800     | 1.542     |
| Min                       | 0         | 0.018     |
| Std                       | 0.189     | 0.277     |

Figure 6. The gap width distribution of hot-press vulcanization made plate

Figure 7. The gap width distribution of autoclave made plate
The gap width distribution of hot-press vulcanization and autoclave made plates is respectively showed in Figure 6 and Figure 7. The horizontal, upper vertical and lower vertical gap width is respectively marked with red, purple and green. The ceramic armor plate fabricated through autoclave process has lower gap width. And the width distribution of autoclave is more concentative too. This indicate that the autoclave method is better than hot-press vulcanization.

5. Conclusion
In practice, direct measurement of ceramic armor plate gaps is not possible. X-ray Detection is the only non-destructive method available to give quantifiable values for gap widths, which are critical to ballistic performance of the ceramic armor plate. This research shows that the X-ray detection method give a good portrayal of array quality, but because of the amplification distortion between the actual gap width with the measured width, the accuracy measurement is difficulty. But the result of this study give us a way to calculate the actual gap width from the measured value, and this is particularly necessary when the ceramic is thick. Since ballistic performance is sensitive to gap width, it is very important to have an accurate and reliable method that can be counted on to obtain correct gaps values.

This study has demonstrated that the ceramic armor plate fabricated through autoclave process has lower gap width than the plate manufactured through press vulcanization. And the width distribution is concentrative too. This indicates that autoclave is a better manufacture method and will has better ballistic performance.

6. References
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