# Computed Radiographic Imaging of Ceramic Body Armour Personal Protective Equipment

Muzibur KHAN [1], Michael BROTHERS [1], Trent GILLIS [1]
[1]Structure and Material Performance Laboratory, Aerospace Research Centre, National Research Council Canada; Ottawa, Ontario, Canada, Phone: +1-613-990-4733, e-mail: muzibur.khan@nrc-cnrc.gc.ca

## Abstract

Ceramic body armour personal protective equipment (PPE) plates and inserts could have defects introduced during: (i) manufacturing, (ii) mishandling, and (iii) operational damages due to projectile impacts. The ballistic performance of armour plates degrade due to the presence of damages and, therefore, the protective purpose cannot be guaranteed. The high cost (manufacturing and raw materials) of ceramic armours has created the expectation of extended service life Non-destructive evaluation (NDE) techniques are required to rapidly and non-destructively determine the integrity and performance of ceramic protective plates for operational deployment. Effective body armor inspection ensures that armour worn by the service personnel is fit for purpose.

Radiographic NDE is capable to visualize and quantify the presence of damages or anomalies and, consequently verify the integrity of the armour plates. Moreover, the computed radiography (CR) uses a reusable phosphor imaging plate instead of film/chemicals is cost-effective and allows for faster image acquisition, improved capabilities for analysis and digital storage. In this study the CR digital images were acquired in universally compatible Digital Imaging and Communication in Nondestructive Evaluation (DICONDE) format and the detected damages/anomalies and their characteristics were tagged in the digital images. Inspection procedure for PPE was developed and optimized aimed to reduce the false rejection of plates and also added an image quality indicator to ensure the optimum setup and quality of inspection.

This is an extensive experimental study which demonstrated that CR imaging using high resolution imaging plates is capable of revealing typical damages in PPE armor plates. It presents the demonstration and validation of CR based PPE inspection processes, along with CR process control mechanism to ensure optimum image quality, high repeatability, while maintain a low false positive call rate. This validated process ensured the traceability and compliance of the inspection being performed.

**Keywords:** Computed Radiography, Personal Protective Equipment, Imaging Plate, Computed Radiography

# 1.0 Introduction

Body armor PPE has been in use for a very long time and is generally related to bullet proof vest worn for ballistic protection to important body parts. A composite is defined as a material containing two or more distinct phases combined in such a way that each remains distinct, and the overall properties are better than of a single material alone. Currently most designs of body armour systems normally consisting of a hard front face of ceramic to provide superior ballistic performance at a light weight and an energy absorbing rear face high performance polymer (e.g. such as aramid or polyethylene fiber) to provide rifle protection. There are also typical armour system such as the Kevlar® vest manufactured by DuPont company, with or without ceramic inserts.

Ceramic plates and inserts might have defects introduced during production, experience service damage resulting from mishandling, wear and tear. In other cases, operational damage may be introduced as a result of projectile impact. The brittle nature of the front face ceramic can be cracked during rough handling. The ballistic performance of armour plates will very likely be degraded due to presence of damage that compromises the effectiveness of the plate The high cost (manufacturing and raw materials) of ceramic armours has created the expectation of extended and effective service life. Currently there is no well understood mechanism or accepted practice for determination life expectancy of body armour and their life span varies significantly. Therefore, it is important to ensure that the structural integrity of the armor is maintained throughout its life cycle, preserved through periodic inspection. Therefore NDE techniques are required to rapidly and non-destructively determine the suitability of ceramic protective plates for combat deployment. Successful body armor inspection ensures that armour worn by troops is both functional and protective.

## 1.1 Non-Destructive Inspection of Armour

Structural complexity and signal dispersion in armour composite materials with many interfaces, including composite materials, can make ultrasonic inspection very difficult. Radiographic techniques (film or digital) are capable to visualize and quantify the presence of damage or anomalies and, consequently verifying the integrity of the armour plates. X-ray radiography is broadly applicable to any material or test object through which a beam of penetrating X or gamma radiation may be passed through the objects and detected, including metal, plastics, ceramics, and composites. With the advent of computed radiography (CR), the use of film radiography is gradually diminishing, since CR allows for fast, reliable and accountable inspections. Film radiography also lack digital advantages such as archiving, enhancement, filter, etc. CR uses a reusable phosphor imaging plate instead of film/chemicals and, therefore, allows for faster image acquisition, improved capabilities for analysis and digital storage, as well as cost savings.

## 1.2 Computed Radiography Inspection of Armour

Industrial radiography is a very mature NDE technique for volumetric investigation and still dominates the industrial and medical imaging applications since the discovery of X-rays in 1895 [1]. Conventional film radiography is an analog process of imaging using penetrating electromagnetic radiation that allows for the internal volumetric evaluation of solid objects and is

well established for industrial NDE applications [2]. Common detecting media currently used for industrial radiography are photographic films (for conventional film radiography), phosphor plates (for computed radiography), fluorescent screens (fluoroscopy) or solid-state flat panel detectors (for digital radiography) [3].

Computed Radiography (CR) was introduced in 1980 [4]. CR emerged as a leading environmentally safe digital technology for recording a radiographic image similar to the ways that film radiography has been practiced for decades [5]. CR is similar to film radiography except that the film is replaced by a reusable photostimulable phosphor imaging plate (IP). The IP has a detector layer of photostimulated crystals containing different halogenides such as bromide, chlorine or iodine [4]. The phosphorous plate is loaded into a cassette and is exposed to an X-ray or gamma ray radiation source. During the radiation exposure, X-ray electromagnetic radiation interacts with phosphor plates, causing electrons charges to be raised and trapped in high energy state in proportion to the received exposure and forms a latent image of the object.

The exposed imaging plate is run through a laser reading device that scans the plate in a raster pattern using a helium-neon laser scanner. Stimulated by a red laser, trapped electrons (during prior exposure) in plates shift to a low energy state and release blue light. This blue light is collected by a light guide and sent to a photomultiplier tube (PMT). The signal from the PMT is amplified, spatially sampled, and converted to a digital signal (analog to digital conversion) and translated into a digital image that is displayed on a monitor for review and evaluation. After reading the plate, the phosphorous screen is erased by the laser scanner and becomes ready for reuse. The process of digitizing may take from one to five minutes depending on the image size and resolution. The digital image can be further processed, analyzed and stored on a computer or other storage media. Digital archiving is simpler and the images can easily be electronically copied, manipulated and distributed [3]. Figure 1 graphically illustrates the key processes involved in CR imaging. Figure 2 shows the CR system scanning setup and Figure 3 presents the X-Ray tube/controller, CR system/image quality control phantom used in CR imaging.

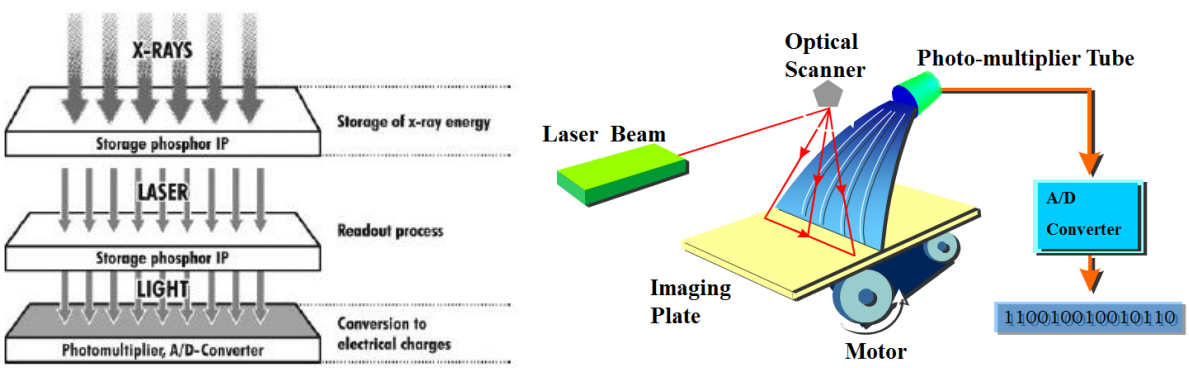



Figure 1: Computed radiography principles based on storage phosphorous plates [4-6]

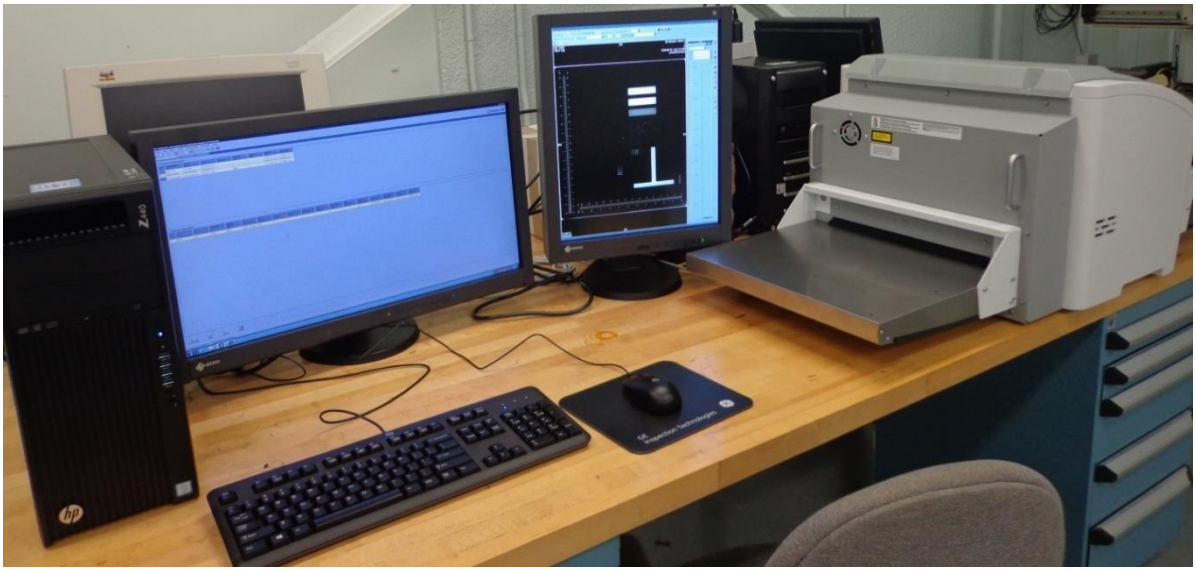


Figure 2: CR system scanning setup

The CR system used in this study are compliant with the Digital Imaging and Communication in Nondestructive Evaluation (DICONDE). DICONDE is a standard for image data acquisition, review, storage, and archival, which ensured image information is recorded along with the image, and all of this information can be viewed on any DICONDE compliant system, regardless of whose system it was acquired on.


Figure 3: X-Ray tube/controller, CR system/image Q/C phantom

### 1.3 Imaging Media

CR systems require the appropriate type of imaging plate for specific applications so that the imaging plates yield acceptable image quality over a wide range of X-ray energy conditions, material types, material thicknesses, and configurations. Imaging plates which are properly

handled and maintained can typically be used up to 1000 times or more. The imaging plate type contributes to the overall image quality and is a key factor in determining productivity [7]. Primarily two kinds of imaging plates (phosphor plates) are used in CR: standard/general purpose plates and high resolution plates. General purpose plates have thicker phosphor layers relative to high resolution plates. High resolution plates (also called blue plate) have blue dye added to the phosphor layer to further improve resolution at the cost of longer exposure time and higher noise. For the armour plate inspection, the standard resolution imaging plates were used.

### 1.4 CR Image Characteristics

Image quality and degree of details that a CR image can reveal are the key performance indicators considered during characteristics evaluation. Image quality is influenced by a large variety of factors originating in the inspected object (material, thickness), the radiation source (radiation quality), the imaging system (detector/plate properties), geometry (X-ray focal spot size, source-to-object distance, object-to-detector/imaging plate distance, scanning resolution, orientation of defects with X-ray beam, exposure (kV-mA, time), operator visual acuity, etc. [8]. The primary metrics for establishing a CR radiography system's performance are its contrast sensitivity or contrast-to-noise ratio (CNR), basic spatial resolution ($SR_b$) and signal-to-noise ratio (SNR) [9].

#### 1.4.1 Contrast Sensitivity

The contrast sensitivity test assesses the ability of the CR system to detect variations in image intensity (represent by pixel value) caused by the variation in specimen thickness due to anomalies [10]. For PPE armour plate inspection, defects such as such as cluster of porosity, chipped ceramic dimple, bits of additional ceramic material, micro-cracks and/or micro-tears voids, dimple missing etc. relying on adequate contrast sensitivity of CR systems. Typically, most of the engineering codes and film/CR related process control documents require that 2% contrast sensitivity must be achieved in radiographic imaging [10].

#### 1.4.2 Spatial Resolution

Basic spatial resolution (also referred to as sharpness or resolution) of image ($SR_b$) is the ability to distinguish between small objects that are close together in digital image or ability to clearly see abrupt changes in an object. Unsharpness is the parameter used to quantify the lack of sharpness and thus quality of an image [11]. The spatial resolution is one of the key parameters to assess the capability of CR system for detecting crack-like discontinuities to measure the imaging performance level of computed radiography systems.

In PPE armour plate inspection, crack indications in radiographs are the recorded local intensity (pixel value) changes of penetrating radiation that are caused by the presence of cracks in the test object. Due to inherent properties of the radiographic method, cracks are fine indication usually of low contrast and sharpness, located on a non-homogeneous and noisy background.

### 1.4.3 Signal-to-Noise Ratio (SNR)

Noise is usually characterized by the term Signal-to-Noise (SNR) ratio and SNR is an indication of the image quality, the higher the ratio, the less obtrusive the background noise. It can be regarded as the signal intensity relative to the CR system noise. In CR the fluctuation of gray values or pixel values is considered as image noise. Noise is any non-relevant signal that tends to interfere with the normal reception or processing of a desired flaw signal, and is a major factor decreasing the image quality. The SNR depends on the radiation dose, voltage, scatter radiation, random variation of X-ray fluence (energy per unit area), system properties as well as properties of imaging plates.

According to the ASTM E2445 procedure, the SNR performance (characterization of image noise) shall be established using; (a) SNR plateau or (b) equivalent penetrameter sensitivity (EPS). Any of the method would provide the exposure versus noise relationship as described [12].

### 1.4.4 Armour plate

The ceramic plate inspected in this study are approximately 10 inches by 12 inches in size, layer of a hard front face of ceramic dimple (front face) and a kind of high performance polymer composite (back face). The body armour chest plates are considered sensitive material in terms of their fabrication and intellectual property, therefore preventing to provides additional details information

## 2.0 Imaging Procedure

The schematic of the experimental setup of computed radiographic inspection armor is shown in Figure 4. Armor chest plates are placed on top of CR phosphor imaging plate with the strike place facing down position. Chest plate positioned catered with the phosphorous imaging plate with its long axis positioned parallel to the long axis of plate. Chest plates were identified using the lead letter tag on top of the plates. To ensure optimum image quality and repeatability of results among various CR systems in accordance with the dynamic range of the individual CR system, a seventeen steps Al-2024 (Aluminum alloy 2024) step-wedge block were placed in the side of specimen and imaging plate. For correct exposure setting, all steps on the Al-2024 step-wedge, with the exception of the two thinnest steps, are required to be visible and equally discernable on the CR image. The exposure setting aimed to yield dynamic range (pixel or grey scale) distributed from 10% to 90% of the maximum pixel value. Two American Society of Testing Materials ASTM image quality indicators (IQI) shim blocks (0.087 inches and 0.062 inches) were placed on top of two steps (0.620 inches, 0.087 inches) to verify that the achieved image quality meet 2% contrast sensitivity which commonly required contrast in most engineering codes in CR process control.

The source to detection (IP) distance were maintained at 60 inches. The exposure (X-ray Voltage, current and exposure time) also adjusted to achieve target grey scale value range on the center dimples of the plates, grey-scale values on the edge portion of the plates and to avoid over exposure which may lead to false rejection.

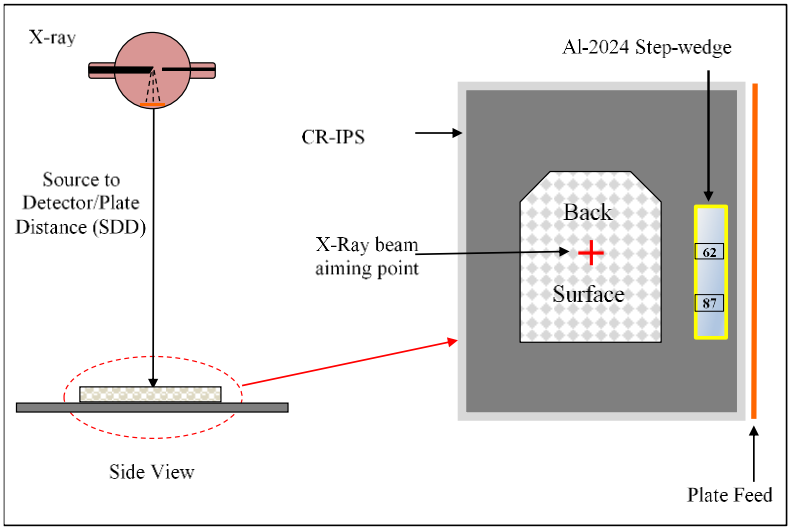



Figure 4: Experimental Setup

## 3.0 Inspection Results

The CR inspection focused on detection and evaluation of defects such as cracks and voids which may have potential impact on ballistic performance. Cracks of varying length may occur anywhere on the plates. Voids may become predominant on the edge portion (flat outer peripheral) of the plates from chipping or breaking through wear and tear. However during the inspection inherent manufacturing process induced anomaly or discontinuity indications such as cluster of porosity, chipped ceramic dimple, bits of additional ceramic material, micro-cracks and/or micro-tears were also noticed in the armor plates. These types of defects are no case for rejection since they were introduced during the manufacturing stage of plates. The plates were accepted or rejected based on pass/fail criteria which was established based on prior ballistic performance test. Any cracks other than craters or micro cracks or missing dimple in the central area of chest plate are reasons for rejection. Indications greater than 1 cm in the edge area of plates also considered as rejection. The underlying reason behind such rejection is that plate's total integrity is compromised because of that kind of defect.

Service induced cracks and voids were primary sources of defects for plate rejection. The cracks profile showed the randomness of crack sizes ranged from few millimetres to the through length or width dimension of the ceramic plates. Ceramic materials have been applied in armor systems for several decades due to its low density, high hardness and compressive strength. However, their brittle behavior and poor tensile strength cause failure and prevent them from absorbing any significant amount of energy [13]. The detected cracks were similar to the conventional linear features found in many brittle, and ductile, materials. The probable causes of cracks were likely pressure of packaging during pressure-cast forming manufacturing stage, or formed in order to relieve local stress or as a result of an external forces (e.g. being dropped or knocked).

Few detected objects at the dimple apparently unwanted objects (e.g. ceramic chips) trapped inside the package from other layers. The probable cause of edge void flaws is chipped edge of the

ceramic due to handling (service or manufacturing). The ceramic particles dropout likely caused due to inaccuracy in molding casting which created multiple small pieces of extra ceramic particle.

No correlation between the crack sizes with usage life of PPE plates was able to establish since the life data was not available. The manufacturing inherent and serviced induced flaws includes porosity, micro-tears or micro-cracks, missing dimples at the edge, trimmed dimple at the edge, small voids at edge (<1cm-diameter), ceramic particle through-out (small unwanted ceramic particles between dimples), gross edge thinning voids etc. also revealed in the CR images. During evaluation, all indications (acceptable and reject able) are annotated in the CR images using the software annotation tools. Sample X-ray of various type of defects are shown in Figure 5 to Figure 7.

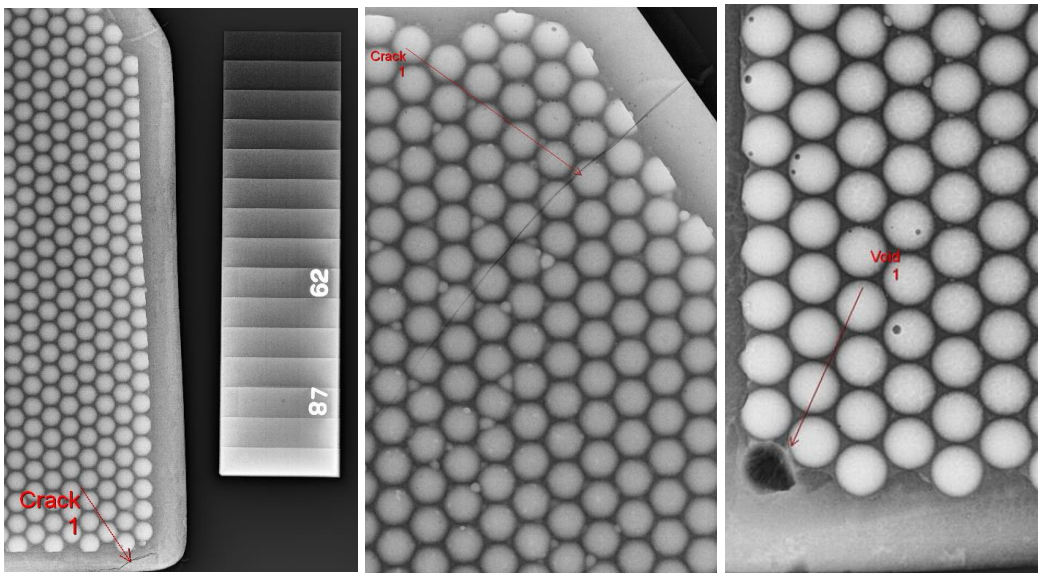
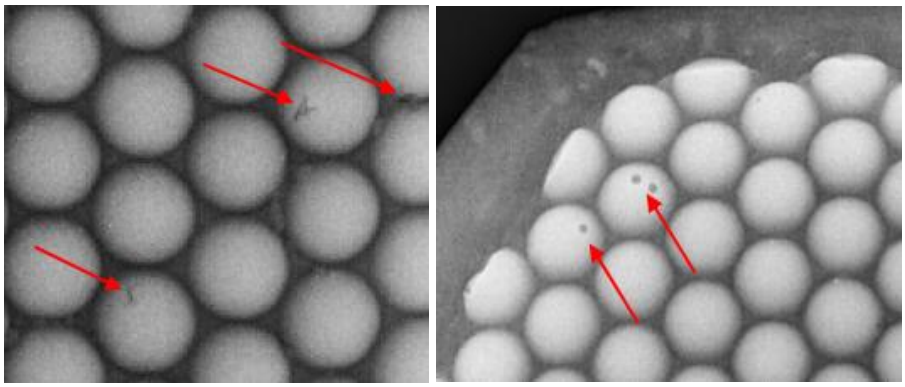



Figure 5: Crack (with step-wedge gauge) and void defect (cause for rejection)



(a) Miro-tears /Micro crack (b) Porosity

Figure 6: Manufacturing discontinuity

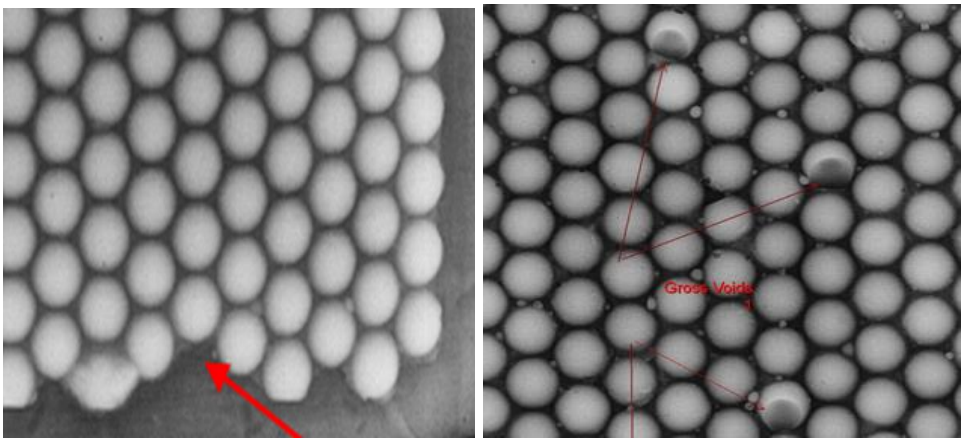



Figure 7: Manufacturing process discontinuity (missing dimple at the edge)

## 4.0 Conclusion

A significant number of PPE plates were inspection, damage types were characterized and evaluated for acceptance and rejection of plates. Cracks and void-like discontinuities in accordance with applicable inspection criteria were the primary causes for rejection of plates. In addition to cracks and voids CR imaging using standard resolution imaging successful were successful in revealing manufacturing inherent and service induced non-critical flaws include porosity, micro-tears or micro-cracks, missing dimples at the edge, trimmed dimple at the edge, small voids at edge (<1 cm-diameter), ceramic particle through-out, gross edge thinning voids etc. In this study, computed radiography demonstrated its capability to provide high throughput in inspection, its unique relative insensitivity to the considerable variations that exist in the design, size and condition of the insert and its covering, various types of damages and overall ability of digital CR to produce an understandable image record of inspected plates for verification purposes. To further advanced the inspection, there is possible plan to apply machine learning/artificial intelligence approach to aid in automatic or semi-automatic damage detection/classification and robotized the inspection.

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