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Experimental study of shot peening and stress peen forming

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ABSTRACT

Shot peening is a cold working process widely used to improve fatigue life of aerospace and automobile components. Stress peen forming is widely used in the aeronautic industry to produce thin components with complex shapes, involving double curvatures, such as wing skins. In this paper, quantitative relationships between the saturation, surface coverage and roughness with respect to peening time have been established based on aluminum Al2024 test strips. The influences of peening velocity and peening time on the resulting residual stress profiles have been experimentally presented. The quantitative relationships between the prebending moment and the resulting arc heights of narrow strips and square strips have been experimentally investigated. Experimental results show that with the increases of the prebending moment, the resulting arc height following the prebending direction increases and the tendency is almost linear. Quantitative equations of the saturation, coverage and roughness as well as the relationship between the prebending moment and resulting arc height can be used for the optimization of shot peening and stress peen forming process.

1. Introduction

Shot peening is a cold working process widely used to improve the fatigue life of metallic components (Harrison, 1987) and to induce curvature of thin aeronautic components, such as wing skins (Burmeister, 1984). Numerous shot peening parameters, such as shot size, type, velocity, incidence angle, material properties of the target component, etc. have a great influence on the effectiveness of the treatment (Kyriacou, 1996). The repeatability of the shot peening process is usually measured using two control parameters: Almen (peening) intensity and peening coverage (Meguid et al., 1999).

Peening intensity is related to the amount of kinetic energy transferred from the shot stream to a work piece during the shot peening process. Almen and Black (1963) introduced a method which is called Almen test to quantify peening intensity. The method consists of peening a standardized SAE1070 spring steel test strip of given dimensions and material that is clamped to a mounting fixture by means of four roundhead bolts. This test coupon, called Almen strip, is of dimensions 76 mm × 19 mm for three commercially available thicknesses: 0.79, 1.29 and 2.39 mm, respectively known as type N, type A and type C. Once the bolts are removed, the Almen strip will curve towards the peening direction. The resulting arc heights under different shot peening times can be measured by a dedicated measuring equipment called Almen gauge. Shot peening saturation is defined as the point on the curve of peening time versus arc height beyond which the arc height increases by less than 10% when the peening time doubles. The Almen intensity, or peening intensity, is by definition the arc height of the Almen strip at shot peening saturation. Complete procedures and specifications of intensity measuring equipment can be found in SAE standards SAE-J442, SAE-J443 and SAE-AMS 2430. Karuppanan et al. (2002) adopted an algorithm for determining the saturation point by means of full regression analysis. They applied Eq. (1)

$$Ah(T) = \frac{B}{(T+d)^p} - \frac{B}{d^p} \quad (1)$$

to fit experimental data, where $Ah(T)$ is the arc height, B, d and p are fitting parameters and T is the peening time.

Coverage is defined as the ratio of the area covered by peening indentations to the total treated surface area, expressed in percentage. Visual inspection is the standard method for coverage evaluation. For practical purposes, the maximum coverage that can be assessed visually is around 98%, since coverage percentages are difficult to discriminate as 100% coverage is approached. Thus, 98% surface coverage is usually considered as full coverage according to SAE J2277. Moreover, 200% coverage is defined as peening twice the exposure time required achieving full coverage. Kirk and Abyaneh (1993) discussed the theory of coverage for random indentations, which assumes that randomly distributed shot particles reach the

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component's surface at a constant rate and create circular indents of constant size. A simplified treatment of that theory based on the application of an Avrami equation is presented as

$$C_{th}(T) = 100 \times (-e^{-\pi \bar{r}^2 RT}) \tag{2}$$

where $C_{th}(T)$ is the theoretical calculated coverage, $\bar{r}$ is the average radius of the indentations, R is the rate of creation of impacts per unit area and T is the peening time.

Karuppanan et al. (2002) expressed Eq. (2) in terms of peening parameters as:

$$C_{th}(T) = 100 \times (1 - e^{-3\bar{r}^2 \dot{m} T/4\bar{A} r^3 \rho_s}) \tag{3}$$

where $\dot{m}$ is the mass flow rate of the shots, $\bar{A}$ is the peening area on the treated component, r is the average radius of the shots and ρ_s is the density of the shots.

Shot peening improves the fatigue life by introducing compressive residual stress in near surface region which hinders cracks propagation. However, the study of Sharp et al. (1994) showed that the projection of shots at high velocity produces indentations on the surface of the treated material and results in an increased surface roughness which reduces the fatigue life of the treated component. Curtis et al. (2003) concluded that the performance of shot peening depends on a tradeoff between its beneficial effects, primarily the compressive residual stress field, and its detrimental effects, mainly the surface roughness. A surface with higher surface roughness presents more irregularities, which act as stress concentrations to accelerate the nucleation and early propagation of microcracks. In practice, surface roughness parameters are often determined with the help of electronic contact instruments. Curtis et al. (2003) calculated an elastic stress concentration factor K_t related to surface roughness as

$$K_t = 1 + 2.1\frac{R_t}{S_m} \tag{4}$$

where R_t represents the maximum peak-to-valley distance and S_m represents the average distance between peaks.

Shot peening of a thin component induces a curvature towards the peening direction. Almen intensity measurement is a common use of this phenomenon. The use of shot peening to induce a shape is called peen forming. It is a dieless process which has been widely used to form various aircraft components since the 1960s (Baughman, 1984).

Conventional peen forming usually induces a spherical shape in the peened component as normal shot impacts create an isotropic effect in isotropic material. For a wing skin, which has a larger curvature in chordwise direction than in spanwise direction, a technique called stress peen forming can be applied. In stress peen forming, the component is elastically pre-stressed before and during peening, either by stretching or bending the component. In the case of wing forming, wing panels can be prebent along the chordwise direction during peen forming. After peen forming, the resulting curvature along the chordwise direction will thus be larger than that along the spanwise direction. It is possible to obtain the target curvature in the chordwise direction with a small curvature in the spanwise direction.

Most of the stress peen forming process is based on experimental trials and errors and few investigations of stress peen forming have been performed to relate the prebending moments or forces and the resulting curvatures. Baughman (1984) introduced the principles of elastic stress peen forming with prebending moment or prestretching force. Barrett and Todd (1984) showed that the elastic prestressing technique increases the maximum compressive residual stress when compared with conventional peen forming. Li (1981) presented experimental results of stress peen forming under different values of prebending moments. Gardiner and Platts (1999) simulated various stress profiles involved in stress peen forming by using temperature profiles.

According to this literature survey, it is possible to list the limitations of the existing studies:

(1) Almen intensity is defined based on Almen strips made of steel SAE1070, which are different from the practical peened components. Therefore, it is impossible to establish a direct relationship between the coverage and saturation of an Almen strips and the material being treated.
(2) Most of the investigations of Almen intensity, coverage and roughness were conducted separately. No direct relationship between these parameters and shot peening time was obtained through experimental investigation.
(3) For stress peen forming, the relationship between the prebending moments and the curvatures of the deformed component has not been studied in details.

The first objective of this work is to experimentally study the shot peening control parameters (saturation and coverage) and shot peening effects (residual stress and roughness) in details. With experimental data, the quantitative relationship between the shot peening intensity, coverage, roughness and peening time on the same target material can be established. In addition, residual stress profiles for different peening parameters, such as shot velocity, saturation peening time, full coverage peening time are presented. The second objective of this paper is to present the effect of the prebending moments on the peen forming results. The relationship between the prebending moments and the resulting arc heights of narrow and square components are obtained.

This article is divided into six sections. Section 2 introduces devices and parameters in the shot peening and stress peen forming experiments performed in this study. Section 3 presents the shot peening results including saturation curve, coverage curve, roughness curve as well as residual stress profiles. Section 4 shows the relationship between prebending moment and resulting arc heights in narrow strip and square strips. Section 5 discusses the experimental results and conclusions are presented in Section 6.

2. Description of shot peening and stress peen forming processes

2.1. General considerations

Shot peening and stress peen forming process were performed using a high precision mobile blasting machine from Baiker AG (model BLAKA-1) combined with a Motoman SV3X Long industrial robot with XRC 2001 robot controller. Ceramic Zirshot Z425 shots with approximate Young's modulus E = 300 Gpa, Poisson's ratio υ = 0.27 and density ρ_s = 3850 kg/m^3 were used in the experiments. During shot peening process, peening nozzle was installed in the horizontal direction and the aluminum strips were fixed in the vertical direction in order to reduce the impacts between the peening shots. Only normal impingement has been considered in this study in order to compare numerical simulation results. The influence of the colliding between each shot has been ignored in this study.

Table 1
Shot peening process parameters.

Case #	Set pressure (kPa)	Set mass flow (kg/min)	Measured shot velocity (m/s)
1	37.9	0.4	34.6
2	96.5	0.4	53.7
3	155.1	0.4	66.2