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Parametric Study of Fixtured Vibropeening

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Abstract: Vibropeening is a surface treatment process, which combines the peening effect of introducing residual stress with the polishing effect of reducing surface roughness in one single process step. Vibropeening equipment induces vibrations into the media to impart residual compressive stresses in sub-surface layers, as well as polishing on the surface of the work piece. In addition to process parameters, such as vibration frequency, amplitude, and media mass, which are well known in literature, this paper will focus on the study of two additional parameters: immersion depth and process time. It was found that the lower-middle section of the vibratory trough produced the highest Almen deflection. Different continuous treatment times were also studied to explore the maximum introducible residual compressive stress state, and it was concluded that an optimal time range is required to achieve the best residual stress profile. The study demonstrates that different process parameters can influence the effectiveness of the vibropeening process, and that these can be potentially optimized for higher treatment capability.

Keywords: vibropeening; Almen strip; residual stress; Almen intensity; nickel-based alloys

1. Introduction

Vibropeening is a new surface treatment process, which can be compared to existing shot peening plus polishing technology. Vibrostrengthening, also referred to as fixtured vibratory finishing, was proposed by Sangid et al. to impart beneficial compressive residual stresses (CRS) on workpieces using steel shots [1]. This form of fixturing the workpiece has shown to increase the efficiency of vibratory processes, by reducing the time taken to achieve the intended output [2,3]. This technology has been studied to be potentially deployed in the aerospace industry to introduce compressive residual stresses without a large amount of accompanying cold work and surface roughness [4,5]. Minimizing the cold work in the material by surface enhancement was postulated to provide substantial benefit in terms of the fatigue performance at an elevated temperature application [6].

The main control parameters of fixtured vibropeening are motor frequency and amplitude resulting from flyweight setting [4,7]. Flyweight setting is defined as the degree of difference between the two unbalanced weights beneath the trough, which causes the trough to vibrate. However, there are more parameters that can influence the performance and effectiveness of vibropeening process, which have been selected from previous operators' experience [8]. For instance, the use of a compound, media mass, immersion depth, treatment process time, and the setup of fixtures are other process parameters. In vibratory processes, specifically vibropolishing, the use of a compound or lubricant and the type of media are key parameters mentioned by Gour et al. to achieve the desired surface properties [9]. Furthermore, the effect of the use of compounds has been confirmed by Ciampini et al., who demonstrated that the Almen intensity is higher with the addition of water or a compound, compared to a dry process without use of a compound [10]. Hence, in this paper, the focus will be on the study of immersion depth and process time on the application on one of the most commonly used, nickel-based alloys in aero-engine component: Inconel (IN) 718.

2. Methodology

Experimental Setup and Measurement Protocol

The experiments were conducted on a vibratory trough manufactured by the company of Walther Trowal from Germany, TFM58/32VP (Figure 1), with a trough size of 580 mm × 320 mm × 360 mm. The trough is equipped with a Polyurethane (PU) lining container and motor, which can drive the trough to vibrate at a controlled frequency and amplitude.

Figure 1. TFM58/32VP vibratory trough.

Different sets of experiments, as described in the subsequent sections, were carried out. After each experimental trial, Almen deflection of Almen strips was measured using an Almen Gage (Electronics Inc, Mishawaka, USA), and the arc height was tabulated. Almen deflection data or arc height was collected at different timings to generate a saturation curve at each setting, using a saturation curve solver from Electronics Inc, USA. The obtained saturation time was used as the exposure time, to verify the corresponding intensity value at saturation point for at least five repeats, with a tolerance of ±0.02 mmN. In this way, the Almen intensity was obtained from the saturation curve. Furthermore, trials with IN718 test pieces were conducted to assess residual stress. The as-received condition of the coupons was similar to the blisk condition of high-pressure compressors (HPC), which were degreased, heat treated, and anodized. The heat treatment steps are Rolls-Royce proprietary information, and hence will not be listed in this paper. The residual stress was measured at the center of the workpiece using an XSTRESS Robotic X-Ray Diffraction (XRD) measurement system from Stresstech Oy, Finland, with layer removal, using electropolishing in steps of 20 μm. A BS EN 15305:2008 test standard was used for XRD measurements, with the parameters detailed in Table 1 below.

Table 1. Key parameters of residual stress measurements.

Parameter	Value
X-ray source	Manganese (Kα)
Filter type	Chromium
Diffraction angle	152°
Collimator size	2 mm (round)
Exposure time	20 s
Psi-tile oscillation	5°
Young's modulus (*E*)	220 GPa
Poisson ratio (ν)	0.300

3. Results and Discussions

3.1. Immersion Depth

Immersion depth is defined as the distance between the media surface layer and the point of interest of the component to be treated. In a media-filled trough, the force exerted on the submerged components will increase with increasing depth, due to the increase in gravitational force of the mass of the media [4]. However, during the vibropeening process, the media moves in a circular pattern due to the unbalanced mass system, and hence it is observed that the force interactions will be different at every media level in the trough.

It is essential to identify the locations inside the trough that have maximum peening forces, so that maximum peening intensity can be obtained on any component that is to be treated. In this study, experiments were conducted on Almen strips using a vibratory trough TFM58/32VP, with the parameters as shown in Table 2. The media used in this study is stainless steel satellite 5/7mm media, as shown in Figure 2 below. The setup configuration is illustrated in Figure 3, with immersion depths labelled. Almen deflection data were collected at 10, 20, 40, and 80 min to generate a saturation curve at each setting, using a saturation curve solver from Electronics Inc. An example is shown in Figure 4. The saturation point is defined as the arc height at time T, where the difference of arc height between T and $2T$ is less than or equal to 10%. The Almen deflection at this time T is known as the Almen intensity. In conventional peening, the Almen intensity at saturation point often has a correlation with residual stress, hence it is an important parameter to be observed in the surface treatment process [4].

Table 2. Parameters.

Experimental Variable	Value
Frequency of trough	1200 rpm, 1300 rpm, 1500 rpm
Flyweight setting	40%, 50%, 75%
Amplitude of trough	3.5 mm, 4 mm, 4.5 mm, 6.5 mm
Compound	Walther Trowal ™ AL01
Flow rate	1.1 L/min
Media type	Stainless steel satellite
Media weight	170 kg
Immersion depths	0 mm, −60 mm, −130 mm, −200 mm
Test piece	Almen strip type N

Figure 2. Satellite 5/7mm stainless steel media.

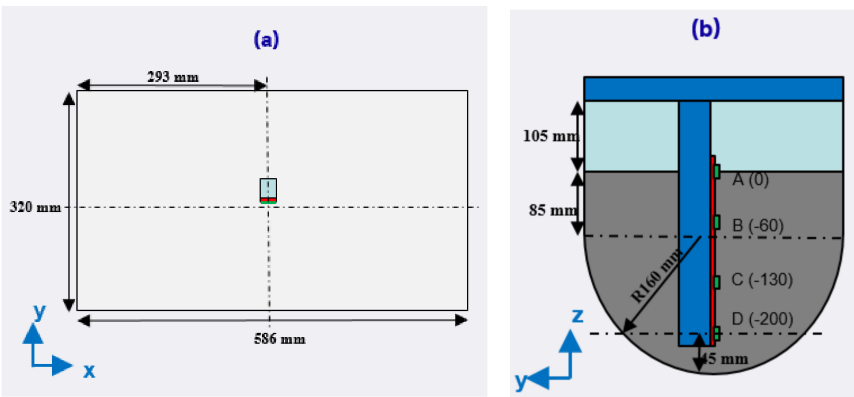

Figure 3. Setup configuration in (**a**) top view and (**b**) side view.

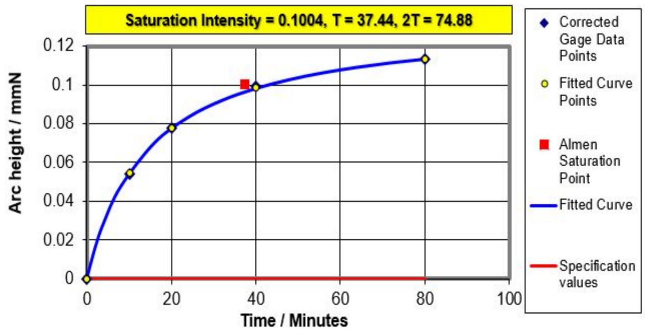

Figure 4. Example of saturation curve.

From the results in Figure 5, the Almen intensity increased when the immersion depth increased from media level 0 mm (point A) up to −130 mm, denoted as point C in Figure 3b; it then decreased when the immersion depth increased to −200 mm (point D). Maximum peening intensity was obtained at the immersion depth of −130mm, which is near the three-quarter of the depth of the trough. This shows that the peening force is concentrated near the lower center of the media rotation, and the burnishing effect is most likely dominant at the bottom of the trough [4]. The trend of the change of Almen intensity is similar at all different combinations of frequency and flyweight settings tested as part of this study.

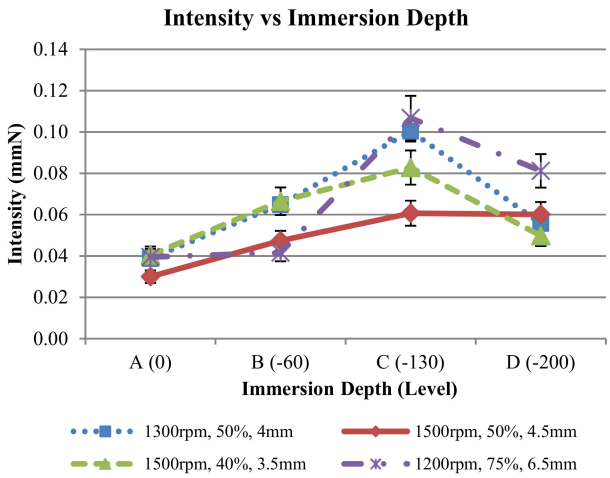

Figure 5. Intensity vs. immersion depth at different settings.

This observation of peening intensity being the best at the middle portion of the trough can be attributed to the interaction of gravitational and vibrational force generated by the media being the most optimal at this position. In an empty trough setup, the main driving force in the trough is the vibrational force generated by the motor and rotating weights beneath the trough, and the trough moving in a circular motion like a rigid body.

A numerical study by Gour et al. proves that the force or acceleration at the top of the trough is dominated in the z-direction, which is purely oscillating translational movement on the z-axis. Towards the bottom of the trough, the acceleration is dominated in both the y- and z-directions, which consists of the oscillating translational movement on the y- and z-axes [9]. Hence, when the trough is filled with media, the resultant forces in the y- and z-directions will drive the media to rotate in circular motion along the x-axis of the trough. The motion of media is illustrated in Figure 6 when the media is experiencing vibrational force by the trough only. For easy reference, the trough is divided into left and right portions, with forces in two opposite directions in each axis. The magnitudes of forces in both directions is graphically represented by the length of the arrow. It is worth noting that the magnitude of forces in the y-direction change with the depth, whereas the magnitude is the same in the z-direction.

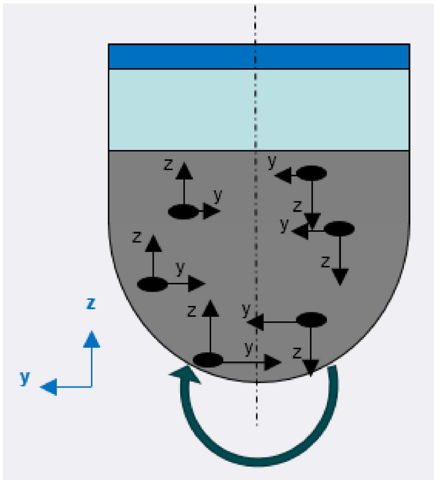

Figure 6. Impact of vibrational force exerted by the trough on a media when rotating (side view).

Gravitational force exerted by the mass of media is another driving force in a media-filled trough. Hydrostatic force can be expressed by Equation (1) below, where h is the depth of media or immersion depth, ρ is the density, g is the gravitational acceleration, and A is the contact area between the media and the component surface. Even though hydrostatic force is experienced in liquids, a similar effect will be experienced in the trough at varying immersion depths.

$$F_h = h\rho g \cdot A \tag{1}$$

As the immersion depth increases, the force exerted by the media increases. Hence, there is always a downward force component in the z-direction throughout the media. With the combination of the vibrational forces, the resultant force increases with depth, hence the peening intensity increases as the immersion depth increases. However, at the immersion depth of −200 mm, which is the depth closest to the bottom wall of the trough, the media at the bottom-most layer of the trough is experiencing the highest impulse from the vibration of the motor, just beneath the trough wall in the upwards direction; hence, the resultant force at the bottom layer decreases and produces a lower peening intensity. The changes in resultant force along the depths are illustrated in Figure 7. There could be a threshold point, where the resultant of all interacted forces is the maximum; however, this exact point could be varied by various parameters, such as media mass, media type, component dimensions, etc. Therefore, the standard immersion depth for most of the test components in the vibropeening trough should be near the lower mid-section region, in order to obtain the maximum peening effect.

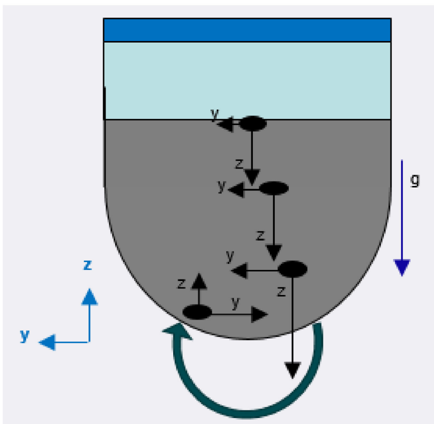

Figure 7. Combination of the forces in a trough along the depths (side view).

3.2. Process Time

The changes in Almen deflection always follow an exponential increment, which increases in value and subsequently reaches a plateau at the saturation point, as shown in Figure 4. Hence, the change in residual stress with treatment time is assumed to be the same. There is always a question of how much the component needs to be peened in order to achieve the desired residual stress profile. However, this depends on the properties of each material, such as elastic modulus, hardness, and ductility, to name a few. Therefore, it is important to determine the saturation point of the treating material to avoid over-peening, when the residual stress profile will not have any improvement further or will even deteriorate [5].

The process time or treatment time for the vibropeening process is normally selected based on the saturation time from Almen intensity test. The correspondence relationship between Almen intensity and residual stress has been proven in the shot peening process [8,11]. However, for the vibropeening process this is may not be the case, due to different mechanisms of the two processes. Study by Canals et al. proved that the increase of peening time to twice the Almen strips' saturation time showed increase in compressive residual stress profiles of materials Ti-6Al-4V and E-16NiCrMo13, but no further increment with thrice the saturation time [7]. Hence, in this study, the saturation time of the vibropeening process with a fixed set of experimental parameters is determined using IN718 flat test coupons. This can provide the suitable range of process time and help to identify the maximum treatment capacity of the vibropeening process. An Almen intensity test has been conducted prior to the flat coupon's trials, and the time for studies is chosen based on the saturation time from the intensity tests.

The study was conducted using IN718 flat test coupons in a TFM58/32VP trough by Walther Trowal, Germany. The experimental setup and coupon location are illustrated in Figure 3. The experimental parameters for this study are shown in Table 3. The flat coupons are wire-cut from the heat-treated IN718 disc bore. The coupon dimension is 30 mm × 40 mm × 4.5 mm, as shown in Figure 8.

Table 3. Parameters.

Experimental Variable	Value
Frequency of trough	1500 rpm
Flyweight setting	50%
Amplitude of trough	4.5–5 mm
Compound	Walther Trowal ™ AL01
Flow rate	1.1 L/min
Media type	Stainless steel satellite
Media weight	170 kg
Process time	1 h, 2 h, 4 h, 8 h
Immersion depths	0 mm, −60 mm, −130 mm, −200 mm
Test piece	IN718 flat coupons

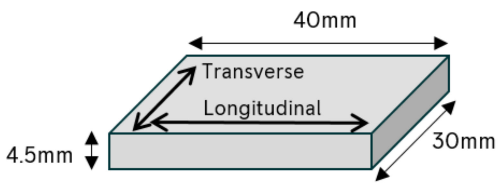

Figure 8. IN718 flat coupon dimensions.

From the observation from part A and the residual stress results, the optimal treatment intensity from vibropeening is at an immersion depth of −130 mm. Hence in this section, the focus of discussion will be on this media level. The residual stress profiles of IN718 test coupons at an immersion depth of −130 mm are shown in Figures 9 and 10. The corresponding full-width at half-maximum (FWHM) distributions also plotted in Figures 11 and 12.

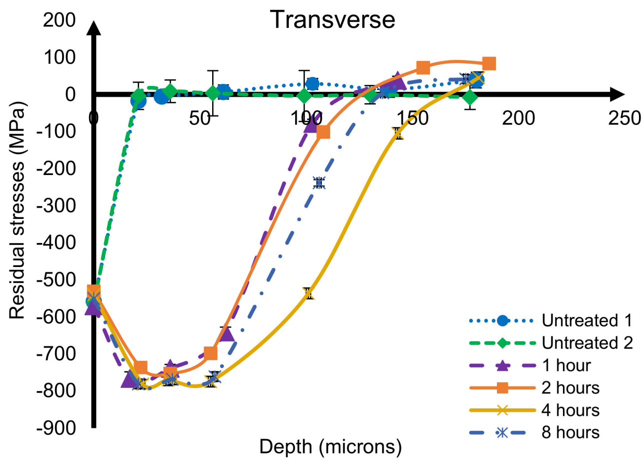

Figure 9. Residual stress profile of IN718 at −130 mm in the transverse direction.

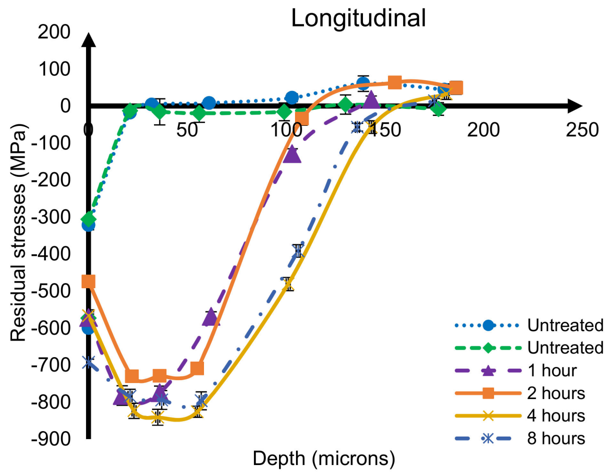

Figure 10. Residual stress profile of IN718 at −130 mm in the longitudinal direction.

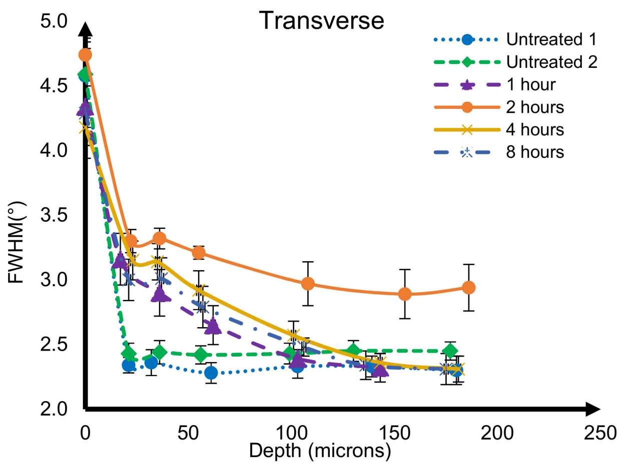

Figure 11. Full-width at half-maximum (FWHM) distribution of IN718 at −130 mm in the transverse direction.

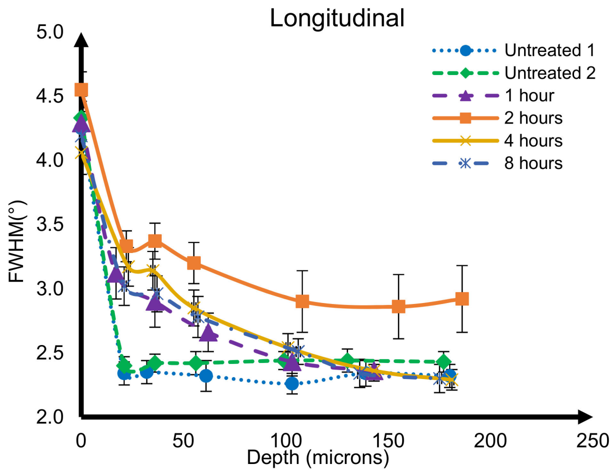

Figure 12. FWHM distribution of IN718 at −130 mm in the longitudinal direction.

From Figures 9 and 10, high compressive surface residual stress can be observed on the untreated coupons, which is due to the manufacturing process. However, the high stress state only occurs at near-surface depths. A stress-free state can be observed at depths beyond 20 microns. The flat coupon after a treatment time of 4 h showed higher surface and maximum compressive residual stress, and a greater depth of influence compared to that of 2 h in both the transverse and longitudinal directions. When the treatment time increased from 1 h to 2 h, the residual stress profile becomes better in the transverse direction. This result is aligned with the hypothesis, which is that the residual stress state is better with longer treatment time. In the transverse direction, the surface and maximum compressive residual stress after 8 h treatment time is similar to that of 4 h, but the depth of influence after 8 h is shallower. This indicates that the impact of vibropeening with 8 h treatment time have reduced in intensity or energy, or that the imparted stress has possibly been relaxed after 8 h. On the other hand, in the longitudinal direction, the residual stress profile after 4 h treatment time is better than 8 h, with higher maximum compressive residual stress and a greater depth of influence. This proves that there could be stress relaxation with longer treatment time, which could negate the positive impact of vibropeening on the components [5]. This is essential to provide an understanding of the optimal process time for vibropeening.

In addition, full-width at half-maximum (FWHM) is obtained from the XRD measurements, and represents the peak broadening under plastic deformation; it could be analogous to plastic strain. It is known that the values of FWHM are closely related to those of percentage cold work introduced by surface enhancement process into a workpiece [4,8,12]. From Figures 11 and 12, FWHM distributions show that the plastic deformation on IN718 coupons after 2 h treatment time is higher compared to that after 1, 4, and 8 h in both the transverse and longitudinal directions. This showed that higher plastic strain and dense dislocation network is generated after 2 h, and the recovery of plastic strain and dislocation annihilation occurs after 4 h and 8 h of treatment time. The lower FWHM of the flat coupon after 1 h treatment time showed that the plastic deformation is not saturated yet, and it increased when treatment time increased to 2 h. The plastic deformation at depths beyond 120 microns after 4 and 8 h has been annihilated to be the same as that of the untreated condition. Similar FWHM distributions can be observed in the study by Kumar et al. after thermal relaxation on Udimet 720Li [12]. This implies that after 2 h of the process, the cold work has been reduced due to stress relaxation. Hence, the optimal process time of vibropeening treatment on IN718 material should be between 2 to 4 h.

With these stress profiles, it is very likely that the fatigue life of treated components can be increased by peening at optimal time. High cycle fatigue (HCF) is linked to the compressive residual stress profiles generated on the material [1]. Studies by Feldmann et al. demonstrate that high cycle fatigue life can be improved by 35% by the vibropeening process, whereas the shot peening process increased by 61% [4]. It is unclear about the treatment time in that study, but with the current findings there is a potential that HCF of components can be further optimized at the optimal process time to be similar or better than that of shot peening.

4. Conclusions

In this experimental study, the impact of immersion depth and process time have been assessed on Almen strips and Ni-based alloys using vibropeening trough TFM58/32VP from Walther Trowal, Germany. It was found that the section near the lower-middle section of the vibratory trough produced the highest peening intensity, due to the combination of vibrational and gravitational forces in the trough. In addition, the longer the process time, the better the compressive residual stress profile on the treated component. However, there is no further beneficial impact of vibropeening after the optimal treatment time is achieved, whereby after this the stress state of coupons will be saturated. The imparted stress will not increase with further peening, and might even experience relaxation due to over-peening. This also shows that there is a maximum introducible compressive residual stress state for a given material for the vibropeening process.

The authors, through this study, have therefore investigated two key important parameters concerning vibropeening: immersion depth and process time. The study aims to establish that for every given experimental setup, there is an optimum depth at which the best peening action takes place (at the center of the bulk of the media), which is not necessarily at the bottommost point of the vibratory container (as in the case of vibropolishing). As with process time, this is the first time that the authors have proposed the study of using flat coupons as a means to calculate saturation time, as Almen strips may not necessarily be the best means to quantify vibropeening process. The authors, through this study, thus establish that there is an optimal time for every experimental setup. This is particularly useful for industries to peen at the desired process time, and save costs accordingly by avoiding higher cycle times, as well as the adverse effects that may come about by over-peening.

5. Future Steps

Based on the current findings of the study of these two parameters in fixtured vibropeening, there are several questions and theories that would need more detailed experiments to further prove the statements. The variation of the resultant forces in the trough during the vibropeening process has been reasonably explained, based on visual observations and the results of the Almen strips. However, future investigations can be focused on the measurement of impact force from the media, using sensors to quantify the change in forces at every region in the trough. In addition, more vibropeening experiments can be conducted on flat coupons, with more time settings between the optimal process time range and collecting the residual stress data to identify the best process time. Further studies also have to be carried out focusing on the material analysis, such as metallographic observation, SEM observation, micro-hardness measurements, and surface roughness measurements, in order to quantify and understand the process in depth from material properties.

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