

# Surface nanocrystallisation on Ti-6Al-4V component with a robotic controlled shot peening process

Yijun Liu<sup>1</sup>, David Wimpenny<sup>1</sup>, Ben Mcgrory<sup>2</sup>, Colin Mcgrory<sup>2</sup>

1. Manufacturing Technology Centre, Pilot Way, Coventry, CV7 9JU, UK,

2. Sandwell UK Ltd., 2 Foundry Place, Towcester, Northamptonshire, NN12 6FP, UK,

## Abstract

The present study experimentally investigated the influence of shot peening processing on surface nanocrystallisation in terms of the impact kinetic energy as a function of shot peening coverages. The impact kinetic energy of a single shot peening media varied from 1.8J to 77J, while the shot peening coverage changed from 200% to 1600%. In general, nanocrystallization at Ti6Al4V surface has taken place with all shot peening conditions but with different level of surface damages. Shot peening at lower kinetic energy is beneficial to generate nanocrystalline microstructure to a layer thickness of 5-7  $\mu\text{m}$ , without causing harmful damage on Ti6Al4V surface. However, high impact kinetic energies, especially at higher coverage can cause considerable surface damages in the form of delamination parallel to the surface. Delamination was an accumulating result of micro-voids nucleation, growth and their coalescence to form microcracks in the subsurface region where shear localization and severe plastic deformation took place, as evidenced by superimposed high compressive residual stress level and increased microhardness. Shot peening at a low temperature of  $-21^{\circ}\text{C}$  also resulted in nanocrystallisation, however, further investigation of the beneficial effects expected from the cooling process is still needed.

**Keywords:** Shot peening, nanocrystallisation, residual stress, microhardness, shear bands.

## Introduction

Surface nanocrystallisation through surface mechanical attrition treatment (SMAT) was reported two decades earlier by Zhu et al in 2004 [1]. The authors developed an appropriate vibration device using an ultrasonic transducer to bombard small steel balls on a commercially pure titanium (CP Ti) surface at high frequency. A nanostructured layer of  $50\mu\text{m}$  thick was produced on CP Ti surface with this ultrasonic peening process. Since then, surface nanocrystallisation (SNC) on metal surfaces has become a hot research topic. Fard et al carried out a comprehensive review on SNC via severe plastic deformation [2]. In recent years, the shot peening process has been extensively investigated by the academic world and researchers found it is possible to generate nanocrystallisation on various metals' surface, such as biocompatible magnesium alloy [3], mild carbon steel [4], and stainless steel [5]. However, so far there is a lack of study on adoption of the shot peening process for nanocrystallisation at a commercial scale. An initial attempt was made in this area by us in 2017, with initial results of surface nanocrystallisation on Ni-based superalloy Inconel 718 presented in ICSP13 [6]. Since then, continuous efforts were made and a robotic controlled shot peening process was developed. This newly developed process has a great potential to produce surface nanocrystallisation at industrial scale for the first time. The new system was also integrated with a cooling device that is capable to keep the peened metal surface at around  $-21^{\circ}\text{C}$  because a cooled surface was considered to be beneficial for grain refinement. In the present study, the new system was tested for a parametric study on a commercial Ti-6Al-4V titanium alloy with a wide range of processing parameters.

## Experimental Methods

Ti-6Al-4V test coupons were processed with the newly developed Sandwell 5-axis shot peening process at ambient temperature and at temperatures as low as  $-21^{\circ}\text{C}$ . Surface temperature was measured with a high speed thermal camera, FLIR X6900sc. Shot velocities ( $V$ ) were measured using a Progressive Surface/Tecnar G3 Shotmeter. Different masses ( $M$ ) of cast steel shot were used at a variety of shot velocities in order to produce a wide range of impact kinetic energy (defined as  $0.5 \cdot M \cdot V^2$  of a single media impact) from 1.8 Joule to 77 Joule at a range of coverage from 200% to 1600%. Coverage is a ratio of the area covered by plastic indentation to the complete surface area impacted by shot peening. In normal production, 98% coverage is taken as full coverage. Coverage beyond 100% is defined as the processing time as a product of the time taken to achieve 100% coverage, as described in SAE J2277\_201304. The shot peening process complied with AMS2430U and the shot peening media complied with AMS2431/2F.

The samples for SEM and Optical Microscopy study were polished with Struers's OPS polishing suspension (0.05 microns) and then etched with standard Kroll reagent. Microstructure and deformation bands of the peened samples were examined with Hitachi TM-3000 SEM. Microhardness tests were carried out across the transverse section at a test load of 200g dwelling for 15 seconds. Transverse slices of electron transparent, normal to shot peened surface, were sectioned with a FIB/SEM, the size of a foil specimen is around  $5 \times 6$  microns. Detailed microstructure of the foil specimen was studied with a transmission electron microscopy (TEM, FEI Talos) at 200kV. Residual stress was measured with Stresstech PRISM ESPI system.

## Experimental Results and Discussion

The overall nanocrystallisation results are summarised in Fig.1 for the samples treated at different levels of impact kinetic energy as a function of peening coverage. In general, nanocrystallisation took place on the Ti-6Al-4V surface at all peening conditions investigated in the present study. The main difference observed with SEM is the severity of the surface damages caused by repeated impacts. When the kinetic energy is at a low level, between 1.8J and 3.6J, a uniform nanocrystallisation layer was readily generated on the surface without causing visible damages. It is also interesting to find out that the surface treated at low kinetic energies was maintained at good condition even when the coverage increased from 200% to 1600%. With the increase in the kinetic energy to the range of 14J to 77J, nanocrystallisation continues to take place. However, modest surface damage started to appear at the lowest coverage of 200%. Further increase in coverage beyond 200% resulted in more severe surface damage. Both the modest surface damage and the severe surface damage are undesirable features for commercial engineering components.

Fig.2 shows the effect of the coverage on microstructure in the subsurface region. When the surface was peened at a low kinetic energy of 1.8J at a coverage of 200% (Fig.2a), the grain boundaries of the beta phase (in bright colour) were disintegrated, kneaded together with the alpha phase (in grey colour). Ultrafine microstructure of 5-7  $\mu\text{m}$  thick was formed at the surface. When peening was extended to a coverage of 1600%, the plastic deformation and the microstructural evolution did not seem to extend to a larger depth in the subsurface region (Fig.2b). This may be due to the fact that the surface was worked hardened and mechanically strengthened and any further impacts at low energy level was not sufficient to generate any deeper penetration of plastic deformation in the subsurface.

Fig.3 shows the influence of the kinetic energy on surface microstructural evolution. At the standard coverage of 200%, the increase in kinetic energy to 3.6J did not generate a larger depth of the ultrafine grain structured region than that at 1.8J. However, the subsurface region experienced a more severe plastic deformation at a larger depth than the 1.8J case. A contrasted interface boundary was formed between the top blended region and the subsurface region. This is very similar to the nanocrystallisation reported by other authors in this area [7]. There was no apparent surface damage observed in the low kinetic energy cases of 1.8J to 3.6J.

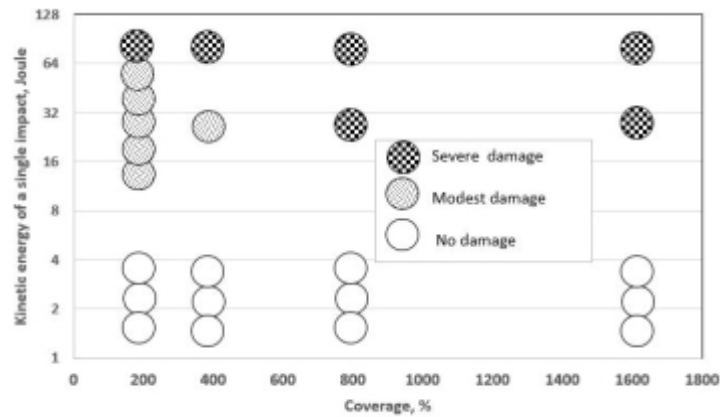


Fig.1: Nanocrystallisation at different impacting kinetic energy as a function of coverage.

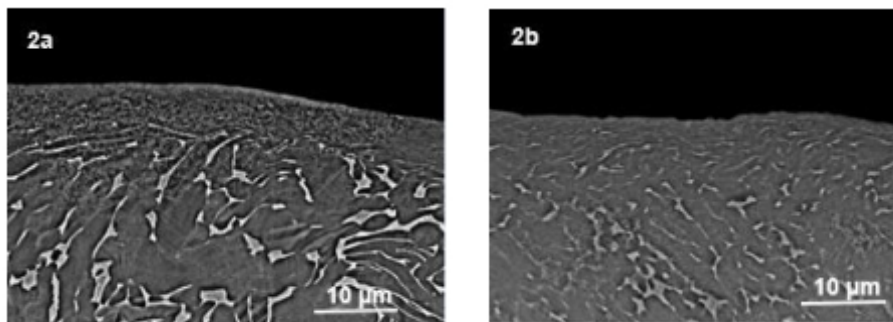


Fig.2: Microstructural evolution in the sub-surface region of the sample peened at kinetic energy of 1.8J at coverages of (a) 200%, (b) 1600% respectively.

When the impact kinetic energy or coverage increased further, a nanocrystalline layer was continuous to form, however, damages at surface and subsurface took place in the form of delamination as shown in Fig.4. When the sample was peened at a higher kinetic energy of 57J for extended period, a single or multiple delamination took place parallel to the metal surface in the subsurface region at a depth of 20-30  $\mu\text{m}$ . Small shear bands or a large single and well developed shear band were formed, as circled with dashed lines in red colour. It looked featureless within the shear band zone. The so-called featureless phenomenon is due to the presence of equiaxed ultrafine submicron or nanocrystalline structure, which provided a direct evidence of dynamic crystallization rather than a boundary migration. Dynamic crystallization took place via a rotational mechanism during a rapid plastic deformation in a very short time at a microsecond scale caused by high velocity impact. This rotational dynamic recovery and recrystallization was similar to what was observed in the Ti6Al4V by Xue et al [8]. Dislocations were accumulated within the shear bands where voids nucleated as a result of high tensile stress in the location. Coalescence of multiple voids then formed microcrack, which was evidenced by the presence of the voids along the edges

of cracks in Fig4. Microcrack then grew and propagated to the voids at its tip, leading to a complete delamination parallel to the surface. The mechanism of this kind of damage is also similar to the surface worn mechanism governed by the work hardening law as reported by Zhang et al [9]. Hence, the critical thickness of the nanocrystallisation layer at the surface is a competition between the magnitude of the work hardening within the shear bands in the subsurface region and the dynamic impacting force that applied on it. The increase in microhardness and the high compressive residual stress at the surface and the subsurface zone are the indications of the work hardening and plastic strain.

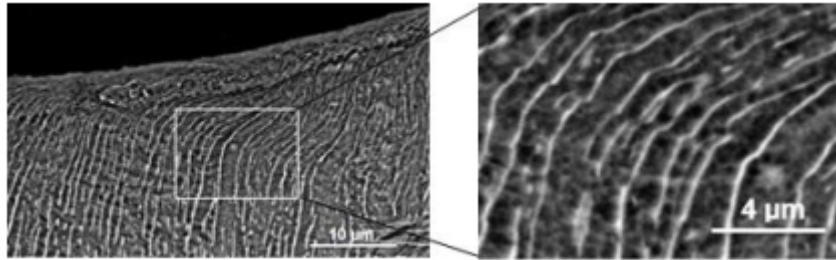


Fig.3: Ultrafine grain structure layer at surface (Left) and severe plastic deformation in the sub-surface region (Right) of the sample peened at 3.6J at a coverage of 200%.

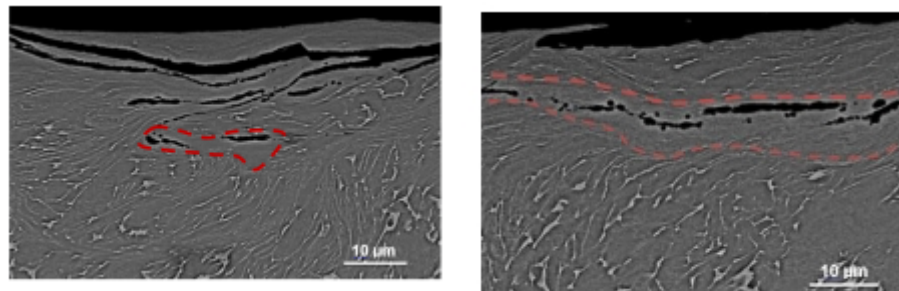


Fig.4: Delamination took place at kinetic energy of 57J at a coverage of 1600%.

Fig.5a shows typical microhardness profiles of the subsurface region shot peened at 200% coverage but with kinetic energies of 1.8J, 14J and 39J, respectively. The surface microhardness increased by around 15-20% in general, but no detectable difference was observed between different kinetic energy levels. It is worth noting that it was not possible to perform the Vickers hardness measurement in the very top surface region of 5-7µm. Hence, the hardness profiles in Fig.5a was not a measurement of the nanocrystalline layer, but they revealed the general work hardening effect in the subsurface zone, which took place at a depth of around 200 µm in the present study. Fig.5b shows the residual stress distributions as a function of coverages when the kinetic energy is 1.8J. A large compressive residual stress was produced by shot peening with all coverages. The depth of the compressive stress area is around 300 µm and was only slightly affected by coverage. The maximum compressive stress falls between 800 MPa and 1000 MPa.

Fig.6 shows the nanocrystalline microstructure observed with TEM when the surface was treated at 1.8J and 2.6J at a coverage of 200%. Microstructure at nanometer scale was generated in the subsurface region at a depth of around 2-3 µm as shown in the bright field images featured by the selected area diffraction ring patterns. The nanocrystallization was not uniform when the surface was peened at low kinetic energy and low coverage. Fine deformation bands mixed with nanocrystals at surface and the subsurface were revealed with EDS mapping in the form of the vanadium rich beta phase boundaries. When the surface was peened for a longer time up to 1600% coverage, the depth of the nanostructured layer was significantly increased up to around 7 µm, as shown in Fig.7a. However, the microstructure still showed the traces of the vanadium rich beta phase

boundaries in both situations peened at ambient temperature and when the surface was constantly cooled down to around  $-21^{\circ}\text{C}$ . Though the nanocrystallisation at  $-21^{\circ}\text{C}$  seemed to be slightly increased for the sample investigated in the present study, the data is insufficient to conclude the benefit that the cooling at  $-21^{\circ}\text{C}$  brought on the nanocrystallisation.

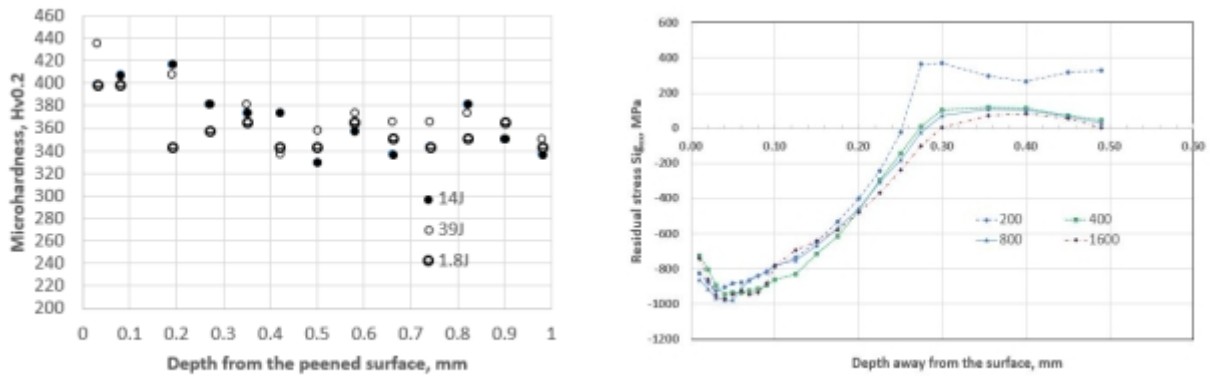


Fig.5: Comparisons of (a) microhardness at different kinetic energy levels at coverage of 200% and (b) residual stress distributions at 1.8J at different coverages of 200%-1600%.

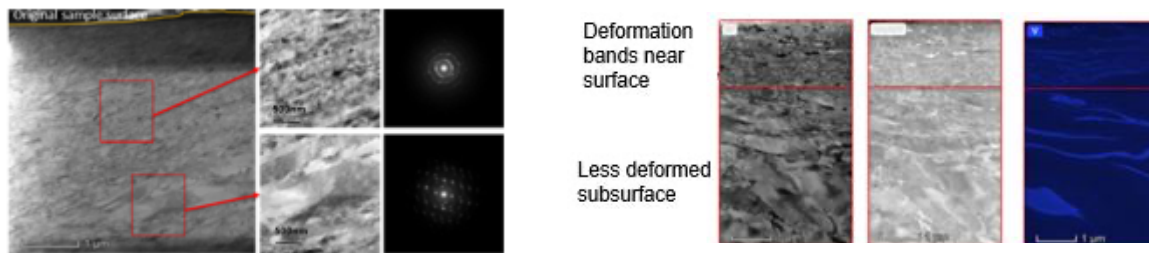


Fig.6: Bright field TEM images and selected area electron diffraction patterns in the subsurface region of the samples peened at 1.8J (Left) and 2.6J (Right) at 200% coverage at ambient temperature.

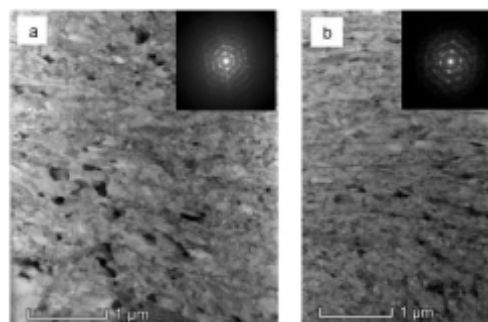


Fig.7: Bright field TEM images and selected area electron diffraction patterns in the subsurface region of the sample peened at 2.6J for 1600% coverage at ambient temperature (a) and constant cooling down to  $-21^{\circ}\text{C}$  (b), respectively.

## Conclusions

Surface nanocrystallisation on Ti-6Al-4V surface was obtained with the new shot peening process at a depth of at least 5-7 microns in the subsurface region. All shot peening conditions have generated nanostructured surface. However, only the low kinetic energy peening can generate useful nanocrystalline layer without causing harmful damages. Peening at high kinetic energy and high coverage all caused surface delamination. Under severe shot peening conditions, voids were formed initially in the subsurface region, then agglomerated and connected one another causing micro-cracks that led to delamination parallel to the surface. Experimentation on surface cooling influence on nanocrystallisation was carried out, however, further investigation is needed in the future development of this new shot peening approach.

## Acknowledgements

The authors acknowledge the support of Innovate-UK fund (70397-487202).

## References

1. Zhu, K. et al., 2004. *Nanostructure formation mechanism of  $\alpha$ -titanium using SMAT*. *Acta Materialia*, Volume 52, p. 4101.
2. Fard, S. B. & Guagliano, M., 2009. *Effects of surfaces nanocrystallization induced by shot peening on material properties : a Review*. *Frattura ed Integrità Strutturale*, 7 (2009) 3-16, Volume 7, pp. 3-16.
3. Bagherifard, S. et al., 2018. *Effects of nanofeatures induced by severe shot peening (SSP) on mechanical, corrosion and cytocompatibility properties of magnesium alloy AZ31*. *Acta Biomaterialia*, Volume 66, pp. 93-108.
4. Maleki, E., Unalb, O. & Kashyzadeha, K. R., 2018. *Effects of conventional, severe, over, and re-shot peening processes on the fatigue behavior of mild carbon steel*. *Surface & Coatings Technology*, Volume 344, pp. 62-74.
5. Jayalakshmia, M., Huilgola, P., Ramachandra Bhatb, B. & Bhata, K. U., 2018. *Insights into formation of gradient nanostructured (GNS) layer and deformation induced martensite in AISI 316 stainless steel subjected to severe shot peening*. *Surface & Coatings Technology*, Volume 344, pp. 295-302.
6. Liu, Y., McGrory, B. & McGrory, C., 2017 pp92-97,. *Nanocrystallisation on the surface of superalloy In718 component with a commercial shot peening process*, 13th International conference for shot peening, Montreal Canada, ICSP13 proceedings.
7. Unal, O. & Varol, R., 2017. *Surface Nanostructuring of AISI*. *Research and Reports on Metals*, 1(3).
8. Xue, Q., Meyers, . M. & Nesterenko, V., 2002. *Self-organization of shear bands in titanium and Ti-6Al-4V alloy*. *Acta Materialia* , Volume 50, p. 575-596.
9. Zhang, J. & Alpas, A., 1993. *Delamination wear in ductile materials containing second phase particles*. *Materials Science and Engineering: A*, 160(1), pp. 25-35.