Corrosion and wear resistance of materials processed by beam-based AM technologies

A technical session at the World PM2022 Congress & Exhibition, organised by the European Powder Metallurgy Association (EPMA) and held in Lyon, France, October 9-13, 2022, focused on the corrosion and wear resistance of materials processed using beam-based Additive Manufacturing. This session comprised three papers which looked at ways to improve these properties – both particular pain points for AM's wider adoption – by way of chemical-mechanical surface polishing, adjusted laser power, and the development of new, wear-resistant alloys for AM. Dr David Whittaker reviews the presented papers.

Chemical-mechanical surface polishing to improve mechanical performance and corrosion resistance

The first paper presented in this session came from Agustin Diaz and Patrick McFadden from REM Surface Engineering, USA, and Matias Garcia-Avila and John Scovill of ATI Specialty Materials, USA, and addressed the surface texture optimisation of metal additively manufactured components by chemical-mechanical polishing to improve mechanical and corrosion resistance [1].

Fatigue performance and corrosion resistance requirements are two of the most problematic aspects in the Additive Manufacturing field. The main reasons for failures in these two aspects are the close relationship between surface texture and the usual surface-related defects (SRD), such as partially melted/sintered powder, v-notches, remnants of melt pools (fish scaling), and remaining support structures. These defects can reduce corrosion performance and cause fracture initiation sites. For most medical, aerospace, space exploration, and many other applications, these defects can limit applicability.

The main objective of the reported study was to showcase a combination of surface finishing techniques developed for metal AM workpieces, capable of improving surface waviness, roughness, corrosion resistance, and mechanical properties under cyclic loading.

Fig. 1 The plenary session at World PM2022 in Lyon, October 2022 (Image PIM International)

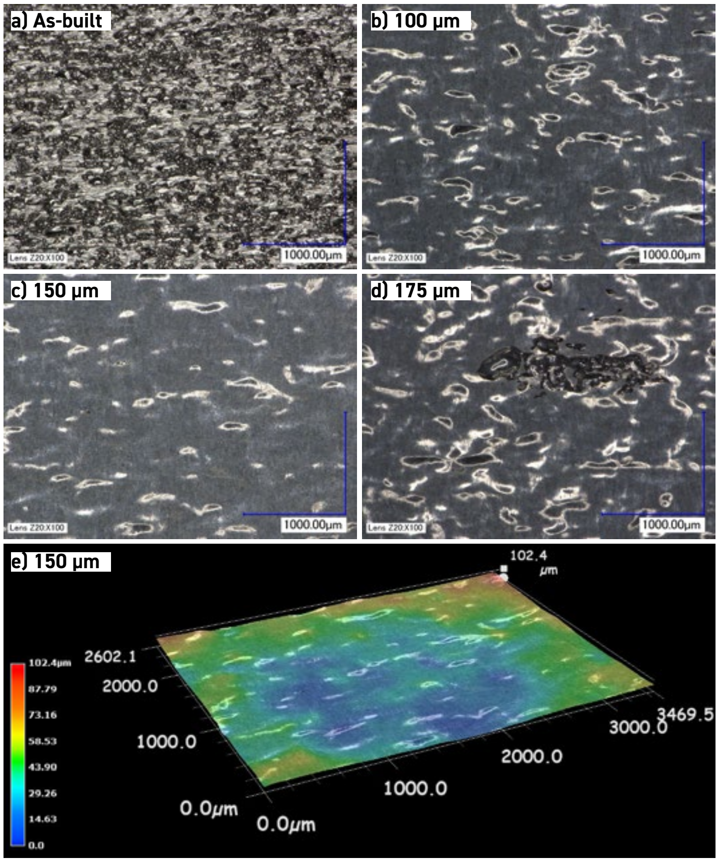

Fig. 2 Microscope images at 100 X magnification of the surface texture progression at different levels of surface material removal of PBF-LB (Ti-6Al-4V), with near-surface porosity problems exposed during the CP process (a–d), and 3D microscope image of the surface at 150 µm surface metal removal (e) [1]

For components additively manufactured via Powder Bed Fusion (PBF), the stress raisers that compromise fatigue lifetime are largely hidden below an accumulation of partially melted/sintered powder at the surface. It is well known that the cause of early failure is the accumulation of stress raisers at the surface, such as extreme surface roughness and v-notches. The other aspect that is often associated with surface roughness is the material's corrosion resistance. Surface texture features in PBF components can be associated with different corrosion issues (e.g., pitting corrosion, crevice corrosion, or fretting). It has also been established that, due to the strong correlation between SRD and the corrosion resistance of components, it can be anticipated that the corrosion resistance would be significantly improved after an appropriate surface finishing operation.

The other aspect that compromises structural integrity of PBF components is the accumulation of sub-surface porosity at the near surface. A contour scan, comprising one or more electron or laser beam passes, can be employed during the build process to delimit the part surface from the part's internal structure. When the contour process parameters are not optimised, sub-surface porosity is generated, reducing the relative density of the material and compromising mechanical performance. Also, there are instances where the issue is not within the contour scan line, but, instead, is within the overlapping settings between the contour and the hatching pass. Failure to produce a successful overlap between these two passes causes sub-surface porosity and lack of fusion at the near-surface. However, this internal porosity can be healed with a proper Hot Isostatic Pressing (HIP) procedure. Therefore, any subtractive surface finishing operation should improve mechanical and corrosion resistance if a post-processing heat treatment capable of remediating the sub-surface porosity, such as HIP, is performed beforehand.

Many of the potential post-process methods for the improvement of surface texture are inapplicable for AM components, because of the technology's freeform capability and resultant complex geometries, including internal passages, cavities and channels.

The reported work has focused on the effects of surface finishing of PBF-built metal components, using a combination of technologies that have demonstrated the potential to eliminate or reduce surface-related defects, involving chemical-mechanical polishing. Examples of such finishing treatments for Electron or Laser Beam Powder Bed Fusion (PBF-EB and PBF-LB, respectively), were showcased to demonstrate the process's capabilities. Case studies for PBF-EB Ti-6Al-4V, PBF-LB GRCop-42, and PBF-LB IN625 were selected as examples.

The specimens used for the study were additively manufactured vertically (90° with respect to the building platform) using the two different PBF types. Specimens were additively manufactured with and without contours.

The surface finishing process was performed by REM Surface Engineering, using their Extreme ISF Process®. This process combines a chemical polishing (CP) operation followed by a chemical mechanical polishing process (CMP). The CP was performed by immersion in a robot-controlled chemical polishing bath. The CMP was performed in a 30 L circular vibratory bowl with a mix of non-abrasive ceramic media. The chemistry and dosing used for CP and CMP, as well as the media mix composition, shapes, and sizes, are the proprietary information of REM Surface Engineering and were not disclosed in the presentation.

Turning to the first of the case study examples, Fig. 2 shows the surface texture progression during the CP process of an PBF-LB (Ti-6Al-4V) specimen with porosity problems at the contour/hatching overlap region. It can be observed that most of the surface-related defects were remediated during the first 100 µm of surface metal removal (SMR) (Fig. 2, top right). The partially sintered/melted powder was eliminated and the surface profile peaks were partially planarised. Further processing eliminated most of the peaks. The deep valleys that were still present were significantly shallower and rounded, with a considerable planarisation level at 150 µm of SMR. At 175 µm of SMR, porosity associated with an unsuccessful overlap between the hatching pass and the contour was uncovered. This could usually be remediated with further processing at the expense of more sacrificial metal. This type of problem can be prevalent if extra care is not taken during the build process. Nevertheless, using a relatively inexpensive, fast, and easy CP process can check if some problems like this, or lack of fusion at the near-surface, occurred during the manufacturing process.

The second part of the surface finishing process is the CMP, which involves using a specialised chemical formulation capable of producing a weak amorphous layer at the surface that is easily removed under minimal mechanical action, such as the media's rubbing action in a standard vibratory bowl, accelerating the surface material removal rate. As a result, there is no need to use abrasive media that can be problematic in specific applications due to the possible introduction of inclusions into the sample's surface and the risk of extra rounding on edges, delicate features, and corners.

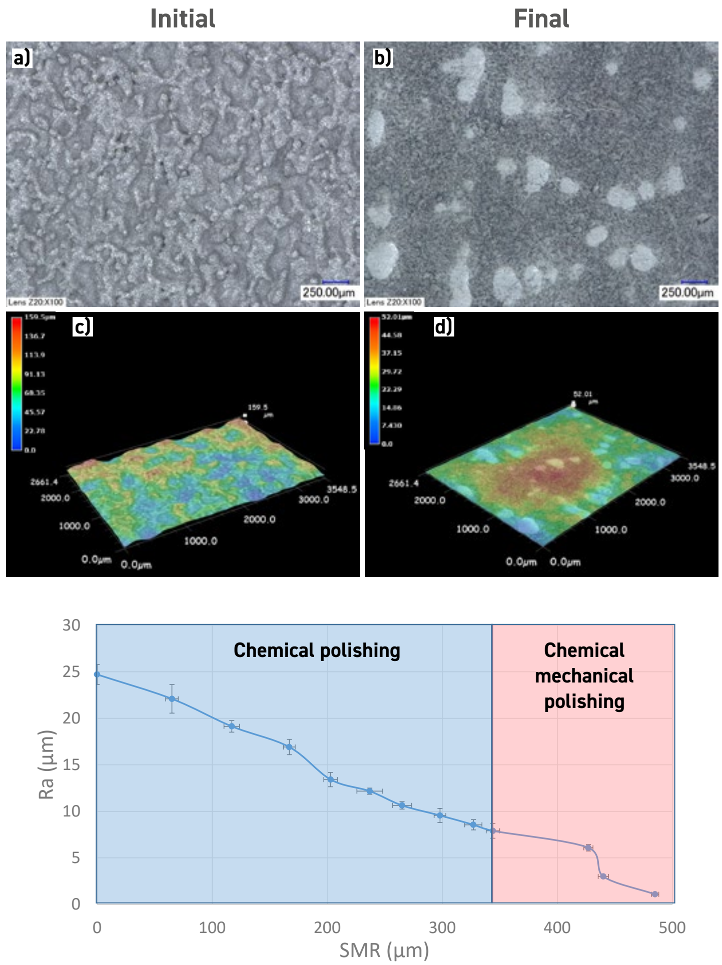

Fig. 3 Microscope images at 100 X magnification (a and b) with their 3D representations (c and d) of the surface of PBF-EB Ti-6Al-4V as-built tensile specimens, and the final surface after surface finishing (b and d). Average surface roughness (Ra) progression per surface material removal through the surface finishing operation (bottom). The blue area on the plot shows the CP progression and the red area shows the CMP progression [1]

Fig. 3 shows the surface texture optimisation progression for PBF-EB Ti-6Al-4V specimens through the surface finishing operations. The as-built components showed typical surface texture features (Ra = 28 + 1 µm) that were eliminated through the CP process by removing 350 µm from the surface. The CP process reached a plateau and no significant change was observed upon further processing. At that point, the specimens were processed by CMP to achieve the required planarisation to target the required Ra. For the HCF (high-cycle fatigue) specimens built with contour and without contour, the Ra target was below 0.1 µm and

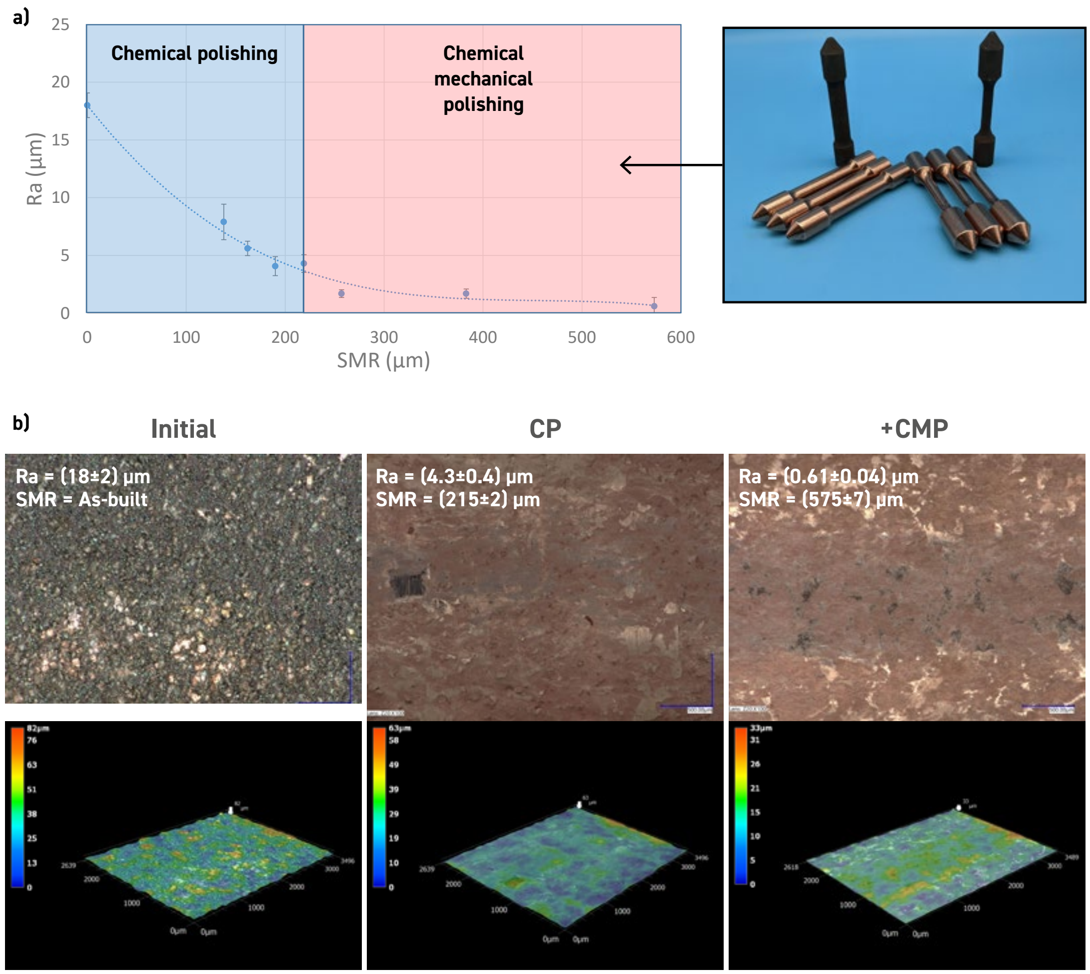

Fig. 4 Average surface roughness (Ra) reduction per surface material removal through the surface finishing operation of PBF-LB GRCop-42, first CP followed by CMP (a). The blue area on the plot shows the CP progression, and the red area shows the CMP progression [1]

Ra = 0.07 + 0.02 µm for the contour specimens and Ra = 0.06 + 0.01 µm for the specimens without contour were obtained with the same SMR of 487 µm. Both samples showed the same surface material rates and level of planarisation. Some random porosity was observed in both samples, even though they were HIPed, probably due to small spots lacking fusion, but these were sporadic.

High-cycle fatigue testing was carried out on the PBF-EB Ti-6Al-4V specimens to study the difference between samples with and without a contour. The results showed that, at 275 MPa, both sets of specimens were stopped with no failure at 1,728,000 cycles, but, for the specimens run at 600 MPa, there was a significant difference in the cycles to failure between the contour specimens (Nf = 22,000 + 9,000 cycles) and the specimens without contour (Nf = 6,000 + 2,000 cycles). This demonstrated the importance of the contour process, where the contour specimens showed a higher fatigue lifetime, even though the contour layer served as a sacrificial layer during the 487 µm material removal.

The second case study focussed on PBF-LB GRCop-42 (Cu-4%Cr-2%Nb). GRCop-42 is a high-strength, dispersion-strengthened copper alloy with excellent conductivity, currently used in liquid rocket engines by NASA and other commercial space companies. Fig. 4 shows the surface texture progression for typical non-HIPed specimens of this alloy through the surface finishing operations. The as-built components show surface texture features overtaken by the partially sintered/melted powder on the surface, with Ra = (18 + 2) µm. The initial surface texture improved remarkably through the CP process; in this specific example, by removing around 200 µm from the surface, a Ra reduction of up to 78% was achieved; followed by the CMP process, reaching the lower possible Ra, where values under 0.6 µm were achieved (Fig. 4).

Finally, the PBF-LB IN625 case study was considered. The surface texture optimisation was performed by removing 400 µm from the surface by CP followed by 100 µm by CMP. The initial surface roughness of the as-built specimens was Ra = (8.3 + 0.5) µm and Ra = (7.5 + 0.2) for the HIPed samples. After applying CP + CMP, the final surface roughness was Ra = (1.1 + 0.6) µm for the non-HIPed samples and Ra = (0.07 + 0.01) µm for the HIPed samples. The non-HIPed sample surfaces showed significant shallow pits from the overall porosity, while the HIPed samples' surfaces were perfectly smooth.

Fig. 5 shows the results of mechanical testing experiments performed on PBF-LB IN625 specimens. The tensile and yield strengths of the specimens were significantly reduced upon HIPing. Nonetheless, the surface finishing process increased these for both non-HIPed and HIPed samples and, in the case of the HIPed samples, the strength lost on HIPing was recovered. However, upon surface finishing, a significant decrease in elongation was observed. The observed effects on the tensile properties can also be associated with the residual compressive stress imparted to the material upon surface finishing. On the other hand, the effects of HIPing and surface finishing on fatigue properties were extremely significant, showcasing the importance of combining surface finishing and HIPing. Surface finished non-HIPed samples did not show a significant improvement in fatigue. The same was the case for HIP samples with no surface finishing.

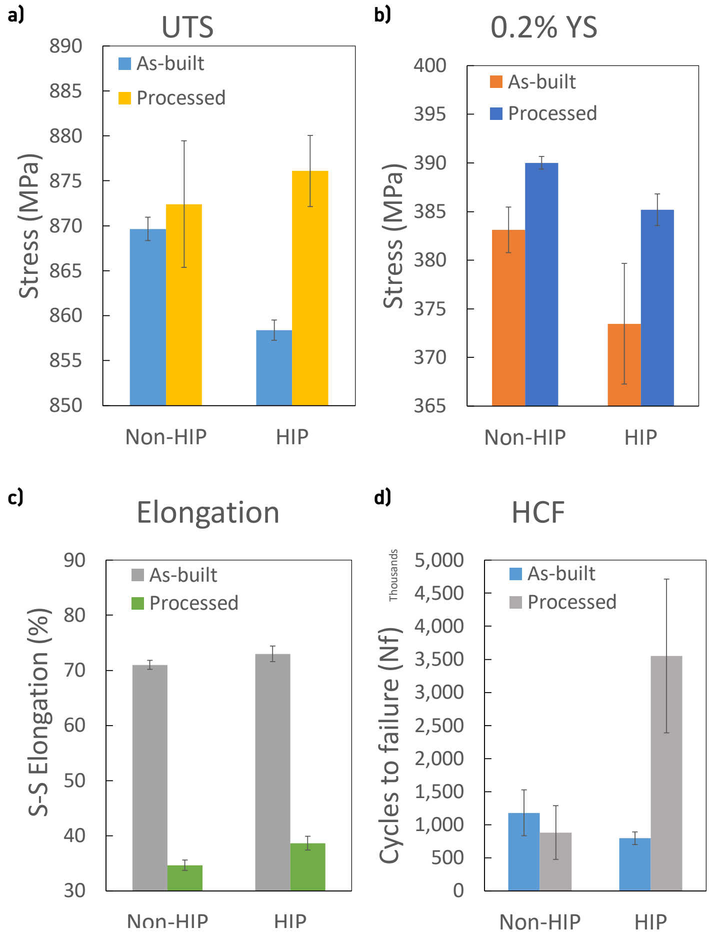

Fig. 5 Tensile strength (a), 0.2% yield strength (b), elongation (c), and uniaxial tensile high-cycle fatigue (Load at 434 MPa, room temperature, R = 0.1, and 60 Hz) of PBF-LB IN625 specimens before and after surface finishing and HIPing [1]

Author and contacts
Dr David Whittaker
Tel: +44 1902 338498
whittakerd4@gmail.com

Agustin Diaz, REM Surface Engineering, USA
adiaz@remchem.com

References
[1] 'Surface Texture Optimization Of Metal Additive Manufactured Components Through Chemical-Mechanical Polishing To Improve Mechanical And Corrosion Resistance Performance,' Diaz, A, et al. As presented at the WorldPM 2022 Congress, October 9–13, 2022, and published in the proceedings by the European Powder Metallurgy Association (EPMA).