Wear behaviour of laser cladded Ni-based WC composite coating for Inconel hot extrusion: Practical challenges and effectiveness

Lynne McINTOSH[a,1], Javad FALSAFI[a], Stephen FITZPATRICK[a] and Paul L. BLACKWELL[a]

[a]*Advanced Forming Research Centre (AFRC), University of Strathclyde, 85 Inchinnan Drive, Inchinnan, Renfrewshire, PA4 9LJ, UK.*

Abstract. In forging, tooling costs make up a significant percentage of the total manufacturing cost. To combat tool failure, forging dies can be manufactured using or including layers of high wear-resistant alloys. The present work compares the manufacturing process challenges and wear response of traditional Nitriding to laser cladding using Ni-based WC on an H13 substrate for IN718 extrusion. The results have shown that machining of NiCrSiB + WC matrix material is problematic, both with regards to cutting tool wear and achievable surface finish. Assessment of pre- and post-extrusion Nitrided H13 and NiCrSiB + 30%WC laser clad dies shows more significant wear features in the case of the additively coated die. Crack formation and surface discontinuities attributed to the effects of material porosity and die heating are also discussed.

Keywords. Laser cladding, forging, extrusion, Ni-based WC, die wear.

1. Introduction

Premature die failure in forging processes results in reduced press availability, extended manufacturing lead times and increased costs associated with die replacement [1]. The opportunity exists to increase die life and reduce die material use for the forging industry to tackle cost reduction across a wide range of increasingly cost-conscious manufacturing sectors. By combining traditional forging tool materials such as H13 steel with hard wearing metal matrix composite (MMC) materials, it may be possible to increase die life compared to the more commonly adopted Nitrided H13. MMC's behave in a unique manner due to the distribution of a hard phase material within a relatively ductile carrier allowing for high compressive and tensile stresses to be transferred and distributed throughout the matrix [2]. Ni-based powders have been studied in other works showing that the addition of Tungsten Carbide (WC) can result in improved tensile properties, microstructure, hardness, and wear performance [3][4]. Although promising, none of these works have presented laser cladded Ni-based WC coatings for forging tool applications where high hardness and wear resistance is crucial at elevated temperatures.

[1] Corresponding Author. lynne.mcintosh@strath.ac.uk

Reported here are the manufacturing challenges and wear behaviours of laser clad Ni-based WC on a H13 substrate compared to more traditional Nitrided H13 tool steel in a comparative IN718 forging extrusion trial.

2. Experimental procedure

2.1. Manufacturing trials

Three sample blocks of hardened H13 (52-54 HRC) substrate material were coated in Ni-based WC using a coaxial powder feed laser cladding system. Thirteen small rectangular laser clad sections ~18 mm x 16 mm were generated to obtain the best quality and suitable thickness by altering variables such as powder WC%, overlap, laser power and number of layers. Two powder compositions were studied accordingly; 70%NiCrSiB 30%WC and 40%NiCrSiB 60%WC – both achieved the target thickness of >1 mm. The visual appearance of both samples was largely uniform, however, small undulations were present within the clad layer – a product of the powder delivery step-over during deposition.

Machining trials were conducted on a DMG MORI HSC 75 5-axis machining centre. The coatings were machined using 3 mm Mitsubishi diamond coated end-mill cutters were used with 2 flute – 25 m/min surface speed, 0.05 mm per flute cutting feed – 0.3 mm step over and a 0.5 mm depth of cut. The cutting of the 60%WC MMC material was very difficult due to the high hardness of the WC particles within the matrix causing catastrophic failure and extreme wear of the cutting tools after the first few cutting passes. Additionally, pores / holes were observed along one edge of the 60%WC clad layer as shown in Figure 1. Machining of the 30%WC also caused premature cutter wear, but the rate of wear was significantly reduced compared to that of the 60%WC machining trial. No surface porosity was observed on the 30%WC sample after machining. It was evident that a harder and more wear resistant cutting tool material was required to machine the Ni-based WC matrix.

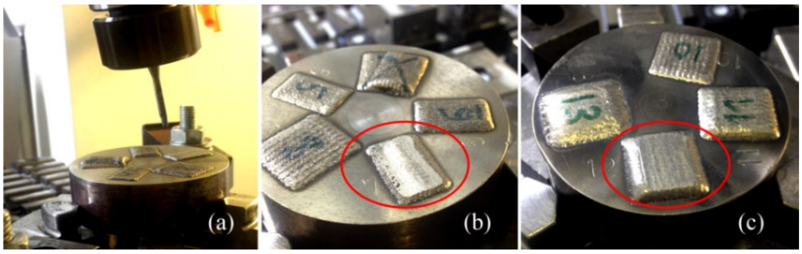

Figure 1: (a) Machining trials (b) sample 7, 40%NiCrSiB 60%WC and (c) sample 12, 70%NiCrSiB 30%WC

Forging trials were designed to compare lower extrusion die wear behaviour of a Nitrided H13 die to a laser clad die during the extrusion of 100-off IN718 billets for each case.

The extrusion tooling was designed in a modular arrangement, this was for two reasons; firstly, to allow the die insert to be easily removed for wear assessment during the trials without removal of the press bolster. Secondly, to allow the die holder and wedge configuration to be used for both the Nitrided H13 and laser clad H13 cases therefore reducing raw material input. Figure 2 shows a schematic of the die design comprising of the die holder, insert and wedge.

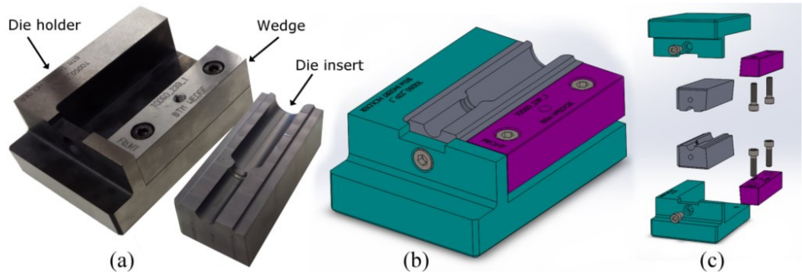

Figure 2: Modular die design, (a, b) bottom die assembly and (c) exploded top and bottom die assemblies.

Machining of the H13 insert was conducted at the Advanced Forming Research Centre (AFRC) using a 5 axis machine centre and standard tungsten carbide ball-nose cutting tools. To manufacture the laser clad insert; first, the H13 insert body was machined as previously described to an extrusion form before laser cladding. The clad layer of 70%NiCrSiB 30%WC was deposited on the H13 extrusion form to a thickness of ~1.2 mm before being returned to the 5 axis machining centre to achieve the final geometry of 1 mm thickness. A small area of under-fill was observed after laser cladding meaning that machining did not clean-up on all surfaces – this is shown in Figure 3(c). Based on sample clad machining trials and further technical advice from cutting tool suppliers, 6 mmØ polycrystalline diamond (PCD) ball-nose cutters at 300 m/min and 0.5 mm per flute were used to machine the laser clad layer to the desired profile. For rough machining, cut depths of 0.1 mm with a 0.1 mm step-over were used and for finishing, cut depths of 0.05 mm with a 0.1 mm step over were used. After machining, porosity and evidence of under-fill were visible on the bearing and extrusion surfaces of the clad insert as shown in Figure 3(c).

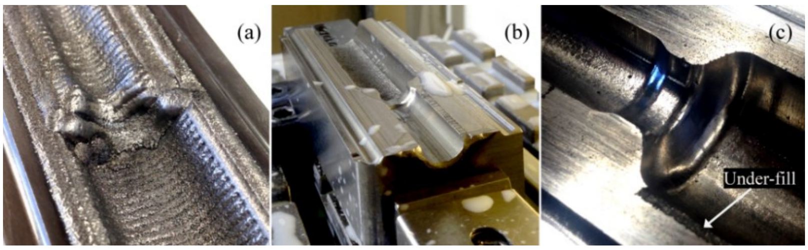

Figure 3: Manufacturing of laser clad insert. (a) Post laser cladding (b) rough machining and (c) machined condition.

Forging trials were undertaken on a Schuler Multi-Forge 500 T vertical and 350 T horizontal double action servo press at 30 RPM and 200 mm/s horizontal stroke speed. Die heating was set to 240 °C and the IN718 billets were heated to 1030 °C for 15 mins in a rotary furnace under protected N_2+H_2 atmosphere. The billets were coated in glass lubricant prior to heating and the dies were lubricated using graphite spray to avoid sticking. After every 20 parts, the bottom insert was removed, cleaned thoroughly and photographed to track visual wear behaviors for the Nitrided H13 as well as the laser clad Ni-based WC insert.

2.2. Dimensional and microstructural assessment

To quantify the wear caused during forging, optical measurement scanning was carried out before and after the forging trials for each case using a GOM ATOS measurement system. This optical 3D scanner provides accurate scans with detailed resolution at high speeds based on digital image processing for industrial components (www.gom.com). Best-fit alignment was used to compare the before and after scans for the Nitrided H13 and laser clad inserts as shown in Figure 4. The neck area and bearing surfaces of the inserts in both cases showed wear patterns with more pronounced surface changes in the laser clad case. Cross-sectional slices of the measured data were analysed and compared around the neck area in further detail.

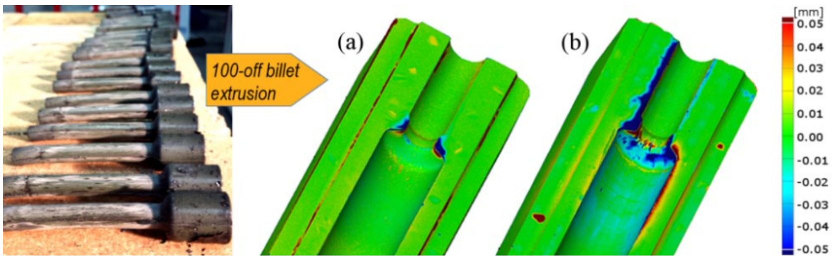

Figure 4: GOM Inspect Analysis Output after forging trials. (a) Nitrided H13 before Vs after forging and (b) laser clad before Vs after forging.

Microstructural assessments were carried out on the cross-sectional surface of the Nitrided H13 and laser clad materials. Sections were cut from the sample blocks using wire EDM before being ground, polished and etched for more detailed examination. A Zwick Roell Indentec ZHμ HD Hardness Tester was used to determine the micro-hardness of the samples whilst an Olympus GX51 was used to carry out optical microscopy investigations. Scanning electron microscopy was also undertaken.

3. Results and Discussion

Periodic removal of the bottom die inserts during the forging trials revealed progressive degradation of both the Nitrided H13 and the laser clad insert across 100-extrusion operations. The visual appearance of the wear in the laser clad case was more pronounced with transverse cracking detected after only 20 extrusions and material collapse in the bearing surface detected after 40 forging extrusions. Cracking is believed to be primarily due to cyclical heating from the billet resting on the insert surface before extrusion, and due to the difference in overall stiffness between the substrate H13 and the clad layer under the compressive clamping load during forging. The material collapse occurred on the bearing surface close to an area of laser clad under-filling suggesting that this pre-existing weakness in the material may have further compromised the clad layer in the surrounding area.

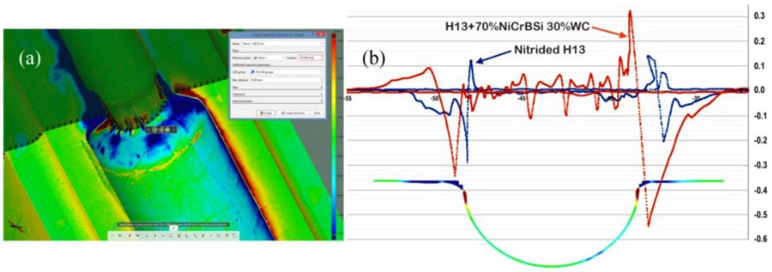

Figure 5: GOM Inspect output. (a) Section analysis after 100 extrusions for 70%NiCrSiB 30%WC case and (b) dimensional comparison of Nitrided H13 vs laser clad inserts.

Figure 5 shows the 3D surface measurement that compares the data before and after forging trials for each insert. The laser clad insert displays more extreme wear behaviors' with excessive transfer of the wear products into the extrusion cavity. As can be noted from Figure 5 an undulating surface was formed by plastic deformation of the ductile Ni-based matrix material whilst the hard WC particles are dragged through the matrix during extrusion. Peaks and troughs are formed as the more ductile material is forced upwards by the hard WC particles as they move through the matrix. Three abrasive wear mechanisms have been presented in other research involving laser clad Ni-based WC layers: (1) microcutting; (2) plastic deformation due to a ploughing action; (3) fracture of hard-phase debris in the matrix materials. In these works, microcutting was observed as the dominant abrasive wear mechanism [5], in contrast to the findings herein where plastic deformation is the dominant wear mechanism.

Scanning electron microscopy of the laser clad material revealed that the Ni-based matrix had been enriched with W and C, which may have made it more brittle. This in turn may have contributed to the material collapse on the bearing surface as previously described.

Microhardness measurement of the clad layer revealed the WC particles to have a hardness of 1600 – 2400 $Hv_{0.1}$ and the Ni-based matrix at 450 – 550 $Hv_{0.1}$. This results in a combined hardness of 700 – 1000 Hv in alignment with the literature [6] [7] [8]. H13 Nitriding treatment generates a 50 – 300 μm thick nitrogen enriched diffusion zone and a 2 – 10 μm thick iron nitride compound layer on top [9] which measured a hardness of 900 – 1100 $Hv_{0.1}$ with the main substrate measuring 560 – 585 $Hv_{0.1}$.

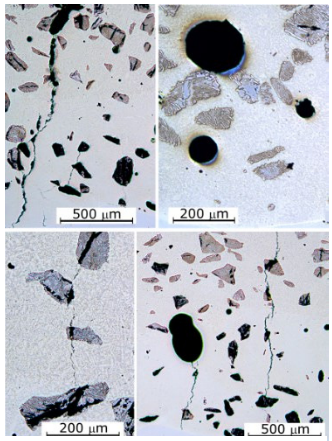

Figure 6: Micrograph of the sample cross-section that shows crack and pores in the Ni-based WC

Optical microscopy of the laser clad material revealed the presence of porosity and cracks as shown in Figure 6. Porosity within the clad layers can be caused by the formation of gas bubbles due to decomposition and transformation of WC trapped in the viscous rapidly solidifying molten pool [4] [10] [11]. Cracks in the clad layer microstructure are mainly caused by thermal stress attributed to differences in thermal expansion coefficients between the matrix and hard and brittle particles such as carbides [8] [10]. The presence of cracks and voids in the microstructure are believed to counteract the advantages of high hardness in the material which would otherwise be effective in counteracting abrasive wear behaviour.

Conclusions

60%WC 40%NiCrSiB matrix material deposited by laser cladding is difficult to machine and caused multiple tool breakages. 30%WC 70%NiCrSiB matrix material deposited by laser cladding, can be machined using conventional 5-axis machines using Poly Crystalline Diamond (PCD) tools.

Degradation of the bearing surface of the insert was more pronounced for the clad insert than for the Nitrided H13 insert. This is thought to be due to the differences in hardness between the WC particulates compared to the Ni-based matrix of the clad material. Wear due to extrusion forging in the die cavity was visually and dimensionally more pronounced in the case of 30%WC 70%NiCrSiB cladded material with maximum peak to trough section measurements showing 0.18 mm deviation. This is an increase of 450% in measured wear behaviour when compared to Nitrided H13 measured at the same position.

Modular die designs such as those generated during this project provide opportunities to industry for cost reduction by enabling material utilisation and tool changeover time reductions.

Acknowledgements

Authors would like to thank the following individuals from the AFRC for their contribution to this work: M. Canavan, C. Cullen, M. Gzyl, L. Hall, W. Kerr, S. Michie, R. O'Neill and S. Rahimi.

References

[1] Dong-Gyu Ahn, Hardfacing Technologies for Improvement of Wear Characteristics of Hot Working Tools: A Review, International Journal of Precision Engineering and Manufacturing Vol. 14 No.7 (2013), 1271-1283.

[2] S.W. Huang, M. Samandi, M. Brandt, Abrasive wear performance and microstructure of laser clad WC/Ni layers, Wear 256 (2004), 1095 – 1105.

[3] J.S Xu, X.C. Zhang, F.Z. Xuan, F.Q. Tian, Z.D. Wang, S.T. Tu, Tensile properties and fracture behaviour of laser cladded WC/Ni composite coatings with different contents of WC particle studied by in-situ tensile testing, Materials Science and Engineering A 560 (2013), 744 – 751.

[4] C. Guo, J.S. Zhou, J.M. Chen, J.R. Zhao, Y.J. Yu, H.D. Zhou, High temperature wear resistance of laser cladding NiCrBSi and NiCrBSi/WC-Ni composite coatings, Wear 270 (2011), 492 – 498.

[5] H. Wang, W. Xia, Y. Jin, A study on abrasive resistance of Ni-based coatings with a WC hard phase, Wear 195 (1996) 47-52.

[6] P. Wu, H.M. Du, X.L. Chen, Z.Q. Li, , H.L. Bai, E.Y. Jiang, Influence of WC particle behavior on the wear resistance properties of Ni–WC composite coatings, Wear, 257(1) (2004), 142-147.

[7] S. Zhou, X. Zeng, Q. Hu, Y. Huang, Analysis of crack behavior for Ni-based WC composite coatings by laser cladding and crack-free realization, Applied Surface Science, 255(5) (2008), 1646-1653.

[8] S. Zhou, Y. Huang, X. Zeng, Q. Hu, Microstructure characteristics of Ni-based WC composite coatings by laser induction hybrid rapid cladding, Materials Science and Engineering: A, 480(1) (2008), 564-572.

[9] T. Björk, R. Westergård, S. Hogmark, Wear of surface treated dies for aluminium extrusion—a case study, Wear 249(3) (2001), 316-323.

[10] C. Lee, H. Park, J. Yoo, C. Lee, W.C. Woo, S. Park, Residual stress and crack initiation in laser clad composite layer with Co-based alloy and WC+ NiCr, Applied Surface Science 345 (2015), 286-294.

[11] J.M. Amado, M.J. Tobar, J.C. Alvarez, J. Lamas, A. Yáñez, Laser cladding of tungsten carbides (Spherotene®) hardfacing alloys for the mining and mineral industry, Applied Surface Science, 255(10) (2009), 5553-5556.