

**Original citation:**

Cooper, D. E., Gibbons, Gregory John, Stanford, M. and Kibble, K. A. (2009) E-Manufacturing for product improvement at Red Bull technology. In: 7th International Conference on Manufacturing Research (ICMR' 09), University of Warwick, UK, 8-10 Sep 2009

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# E-Manufacturing for Product Improvement at Red Bull Technology

David E. Cooper, Gregory J. Gibbons, Mark Stanford, and Kevin A. Kibble

*Abstract*— In Formula 1 racing, there is a strong motive for reducing component weight and thereby improving efficiency. This paper demonstrates the advantages e-Manufacturing brings to the production of hydraulic components. The DMLS production technique would enable weight reductions to be attained by its geometric design freedom coupled with this material's attributes. The use of EOS Titanium Ti64 material for hydraulic components has been assessed by a hydraulic soak test at 25 MPa and no significant losses or failure occurred. The benefits to the efficiency of hydraulic flow have been measured using Particle Image Velocimetry (PIV) and the use of DMLS designed geometry has improved flow characteristics by 250% over that of the currently used techniques of manufacturing channels and bores.

## I. INTRODUCTION

THE process of DMLS e-Manufacturing is one of a number of Additive Layer Manufacturing (ALM) processes in which 3D components or parts are constructed by the layer-additive addition of material directly from CAD data. ALM removes the shackles of reliance on mould tools, and offers the potential for virtually unlimited complexity and design freedom, allowing the manufacture of complex internal structure and freeform geometry. In DMLS (EOS GmbH), a high power laser is used to melt a powder feedstock to form fully dense metallic parts.

The use of DMLS gives design and manufacturing freedom without the restrictions of traditional machining processes, bringing with it the benefit of lighter components, and, for hydraulic components, an ability to enhance internal flow paths, thus greatly improving the flow characteristics and ultimately resulting in less energy demanded of the engine by the hydraulic systems. The additive layer process of DMLS e-Manufacturing in this respect could be advantageous to many component designs throughout the Formula 1 racing environment. Although current F1 race teams are capable of producing a car with a mass less than 605 kg (the FIA minimum [1]), the advantageous weight reduction which is to be gained utilising DMLS would then

allow the designers to apportion the mass gained in other areas or components of the car, to help improve reliability of other components. Currently, most hydraulic components are designed for and manufactured mainly from aluminium billet by 5-axis CNC machining and other processes, typically including drilling and spark erosion.

DMLS technology has moved the concept of Rapid Prototyping [2] into the realm of real time manufacturing of metal components which have been proven for use within some of the most demanding environments and applications to be found [3]-[5]. One attractive aspect of DMLS is that design and production costs do not rise exponentially with the potential complexity of the design [6].

Engineers have been hesitant in embracing DMLS technology having reservations about the material's mechanical integrity, density and the repeatability of the DMLS process. These aspects will be reviewed and discussed in this paper.

Red Bull Technology identified a desire to explore the application of the DMLS process in the design and manufacture of their hydraulic manifolds. The initial research focused on the metallurgical and mechanical aspects of the material, and then to investigate whether the DMLS process could be realistically relied upon to deliver both significantly lighter, and hydraulically more efficient manifolds than those currently produced by traditional methods, without compromising their reliability and safety.

## II. EXPERIMENTAL METHOD

### A. Design and Manufacture

In order to evaluate the use of DMLS for the manufacture of hydraulic components, samples suitable for pressure testing were required. Several test pipes were designed with wall thicknesses ranging from 0.5mm up to 2mm, with different cross-sections (circular, elliptical and hexagonal).

The test pieces (Figure 1) were produced using the EOSINT M270 Machine and were manufactured from EOS Titanium Ti64 powder, by the University of Wolverhampton, using the latest standard build parameters. The parts were orientated as horizontal tubes and were stress relieved at 790°C for 90 minutes and allowed to cool naturally in the furnace before being removed from the Titanium base plate by Wire Electrical Discharge Machining (Wire EDM). The remaining fettling of support structures was performed by CNC milling. In order to pressure test the samples, a thread and a smooth surface finish suitable for a Dowty seal at a pressure of 25MPa, was applied to the boss at each end using a CNC Lathe. The machinability of the

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Manuscript received April 28, 2009. This work was supported in part by Red Bull Technology, EOS UK Ltd, and the School of Engineering, University of Warwick.

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material was found to be good, with standard carbide replacement tooling employed.

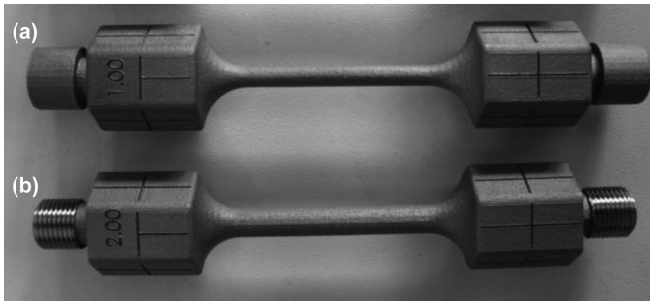


Fig. 1. DMLS parts both pre (a) and post (b) machined.

### B. Pressure Testing

Pressure tests were undertaken to establish whether or not the material could withstand the operating pressure of the race car's hydraulic systems without mechanical failure or losses in pressure due to porosity. A test rig (Fig. 2) was constructed, which comprised a twin walled steel enclosure which served both as an oven (monitored and controlled by two thermocouples) and also as a safety chamber in case of a catastrophic failure. Incorporated in the hydraulic system was an electronic pressure sensor and the system was pressurised by a double acting hand operated hydraulic pump. The system design was deliberately minimalistic with regards to components and connections to reduce potential pressure leaks.

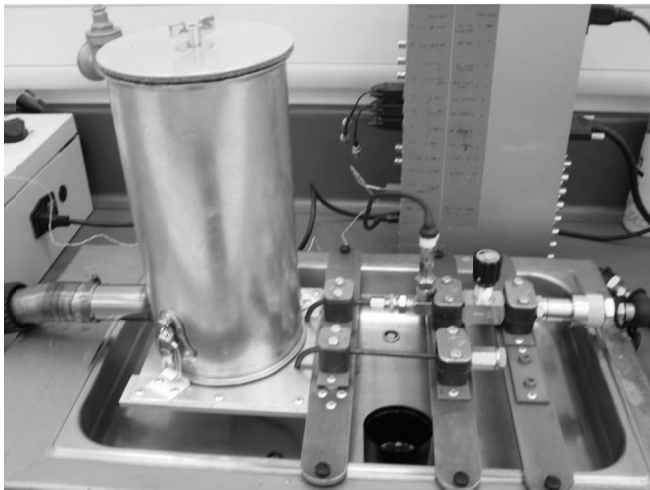


Fig. 2. Pressure test rig, twin walled safety enclosure, pressure sensor & valve.

Each test piece was connected to the hydraulic rig, and the oven temperature was raised to 140°C this being the maximum operating temperature of the hydraulic fluid at a rate of 10°C/min. The pressure was then incrementally raised by 2.5 MPa, held at each level for a period of 2 minutes, and logged through the pressure sensor to a final pressure of 25 MPa this being 3 MPa above the application operating pressure. Once proven at 25 MPa, the pressure was then

reduced to 24 MPa (10% above operating criteria) and left for an extended “soak” test of 20 minutes to observe pressure losses. The thinnest, 0.5mm, samples were also given an extended test of an additional 30 minutes at 24 MPa

### C. Flow Visualisation

A Flow Visualisation study was conducted using Particle Image Velocimetry. This experiment had a twofold purpose, primarily to assess the benefits to the flow, but also to demonstrate the geometric freedom layer manufacturing can provide in producing internal complex flow passages.

The comparative assessments were made by using clear test pieces, manufactured using stereolithography (SLA 5000, 3D Systems Corp) in XC11122 resin (DSM Desotech B.V). One of the test pieces formed with the SLA material emulated an historic example, the second being designed for DMLS.

A pumped closed system was filled with a fluid which matched the refractive index of the SLA material  $n=1.512$  [7] so as to render the flow passage boundaries translucent, removing refractive effects and improving image clarity, thus enabling the camera to image the glass particles. The liquid identified as a match was a Silicone Oil (IMCD UK Ltd) ( $n=1.511$ ).

The passage of glass particles in the fluid was recorded by a high-speed camera. The images were then processed frame-by-frame using the DaVis software suite, correlating individual particles in one frame with the next to obtain a vector for its movement. Using an interrogation window with multiple passes, and decreasing size each pass, provided a best guess window shift from pass to pass and a more accurate correlation on the final pass. [8]

### D. Surface Roughness Measurement

In order to assess the surface roughness of components produced using the EOSINT M270, a Wyko NT 9300 non-contact interferometer (Veeco Instruments Inc) was used to measure the surface at multiple points. The system was used in Vertical Scanning mode, with a measurement area of 611.4 x 465.3 micrometers.

### E. Dimensional Accuracy Measurement

To assess any changes in their geometry and alignment, a dimensional accuracy measurement was made of each sample after building and after pressure testing. Measurement was made using a portable measuring arm (Faro Titanium arm - Faro UK Ltd). The alignment of planes parallel and perpendicular to the sample's axis were probed ( $\pm 0.1$ mm), allowing axial bending and torsional rotation of the samples to be assessed.

### F. Microhardness Testing

Samples cut from representative sample of each production batch were hot-mounted and polished to 1 $\mu$ m. A microhardness measurement was made using a Buehler OmniMet MHT (Buehler GmbH) to obtain the Vickers hardness number. These measurements were used to observe

the consistency of production and also as baseline data for further research on the effects of finishing processes.

### G. Porosity Measurement

Samples were hot mounted and polished to  $3\mu\text{m}$ , hydrofluoric acid etched. Optical microscopic images taken (Olympus Lext confocal microscope). Porosity levels were measured using image analysis software (a4i, aquinto AG, Germany).

## III. RESULTS AND DISCUSSION

### A. Pressure Testing

All of the samples (wall thicknesses 0.5 mm – 2 mm) survived without failure during the test sequence, despite the high pressures applied to them. For each sample, a consistent pressure drop ( $\sim 3\%$ ) was observed during the first 5-6 minutes during pressure application. In the proceeding 20 minute test (at 24 MPa), the pressure remained constant. The initial loss was attributed as inherent in the system, as it was observed across all samples. No statistically significant pressure loss was observed for the 30 minutes extended pressure test for the 0.5 mm wall thickness samples.

### B. Flow Visualisation

Fig. 3 and Fig. 4 show the average vector field across 500 frames for two cases of traditional and e-manufactured geometries. As expected, there are areas of recirculation in the traditional geometry with abrupt changes in direction reducing the flow velocity. This condition is associated with overlapping hole intersections “dead-ends” in the traditional design, an inevitability of the manufacturing, where fluid flow bores are created by drilling straight line holes, and then capping the holes with Lee plugs. This limits the

manufacture of the flow channels to straight lines only, with severe angles between the bores at intersections.

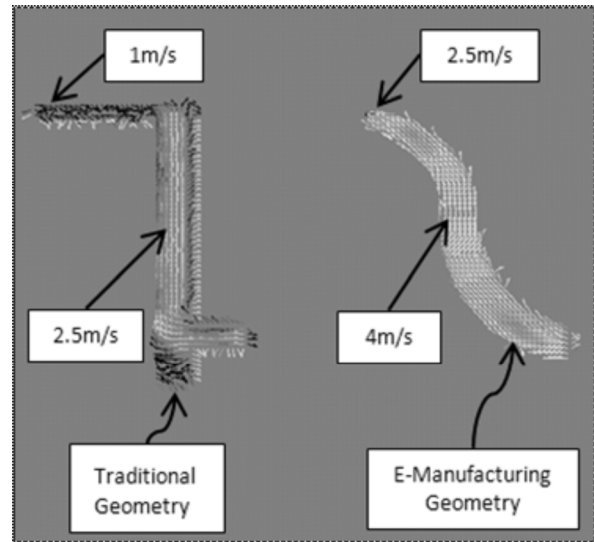


Fig. 4. Vector fields for traditional and e-Manufactured geometry 2.

The measurements of the maximum fluid velocity at the exit and at a centre point of the flow path for the traditional and e-manufactured geometries are given in Table. 1.

Table. 1. Fluid flow measurements for traditional and e-manufactured geometries at centre and end points of the flow path.

Sample	Traditional (m/s)	e-Manufactured (m/s)	$[\Delta\%]$
Fig 3, exit1	1.5	3.0	100
Fig 3, exit2	1.0	2.5	150
Fig 4, centre	2.5	4.0	67
Fig 4, exit	1.0	2.5	150

The increase in fluid flow velocity is significant (up to 150% for end point and 67% for the centre point). This faster flow can be attributed directly to the kinetic energy contained within the fluid. Reduced energy losses during transport will allow more energy to be available at its destination, resulting in a lower energy input from the engine to achieve the same operating effect.

The actual increases in flow rate that might be achieved in a DMLS manufactured component may not entirely compare directly with these PIV results due to differences in the channel surface texture between DMLS and SLA materials.

### C. Surface Roughness Results

Table. 2 gives surface roughness measured at different positions around the test piece, showing significant finish variations dependent upon the location of the face relative to the build orientation. These were consistent over all the test pieces. The upper surface shows the best quality of finish, whereas the  $R_a$  of angled faces was compromised by the stair-stepping effect symptomatic of ALM processing, with

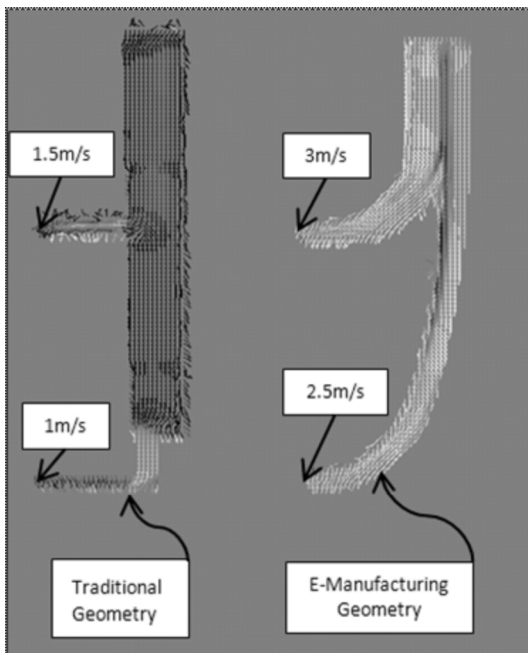


Fig. 3. Vector fields for traditional and e-Manufactured geometry 1.

the downward facing surface found to be rougher than the upper facing surface. The roughest surfaces were those where supporting structures were required for the DMLS build process (in this case to support the tubular section). There may exist therefore a need for post-process finishing to some areas.

Table 2. Surface roughness measurements for the DMLS samples.

Position	R <sub>a</sub> (μm)
Top surface	3.96±0.05
Upper facing sloping surface	8.95±0.05
Lower facing sloping surface	17.50±0.05
Supported surface	27.93±0.05

Good surface finishes are particularly important to hydraulic applications, with union surfaces typically requiring machining to 0.4 μm. Also, smooth surface finishes on internal bores serve to aid in improving flow efficiency, and thus post-processing to improve the finish of internals may be necessary. However, if design and build orientation are carefully considered, the extent of the post-processing required may be reduced.

#### D. Dimensional Accuracy Measurement

Table 3 gives the torsional and axial alignments of the samples, measured before and after pressure testing.

Table 3. Torsional and axial alignments for the DMLS samples.

Sample	Torsional Alignment (°±0.5)			Axial Alignment (°±0.5)		
	Pre	Post	[Δ]	Pre	Post	[Δ]
0.5Tube	1.14	1.31	0.17	0.82	1.07	0.25
0.65Tube	0.69	0.94	0.25	0.7	0.68	0.02
0.85Tube	0.98	0.77	0.21	0.52	1.35	0.83
1.00 Tube	0.34	1.07	0.73	0.39	0.44	0.05
1.25Tube	0.34	0.58	0.24	0.12	1.56	1.44
1.50Tube	0.23	0.75	0.52	0.05	0.33	0.28
1.75Tube	0.49	0.37	0.12	0.13	0.28	0.15
2.00Tube	0.24	0.79	0.55	0.21	0.12	0.09
0.5Ellipse	1.64	2.33	0.69	1.19	0.81	0.38
0.5Hexagonal	0.98	2.38	1.40	0.12	0.53	0.41

Dimensional measurements prior to pressure testing show a slight distortion in the samples. The highest deviations are seen in the thinnest wall section components, most likely from stresses created during the build process due to the large differences in cross-sectional area. Measurement after pressure and temperature testing showed a small increase in torsional and axial, attributable to the torque and forces applied when fitting samples to the test rig rather than to any pressure effects.

#### E. Microhardness

A Vickers hardness of ~350HV was established for pre-heat treated parts, with an increase to ~500HV after heat treatment, remaining consistent across all three production batches. These baseline measurements were conducted to facilitate further research into surface finishing techniques, such as anodising and electro-polishing, to quantify any effect on hardness.

#### F. Porosity

A representative cross-sectional image of one of the e-manufactured components is given in Fig. 5. The areal density of porosity was measured to be 0.28±0.05 %.

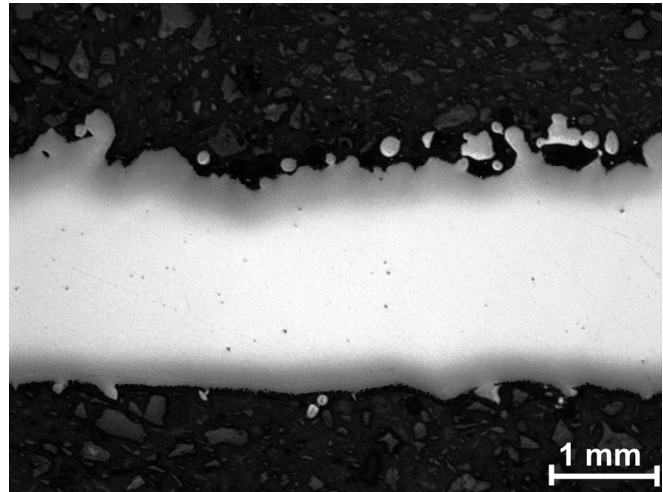


Fig. 5. Optical micrograph of a sample of EOS Titanium 64.

#### ACKNOWLEDGMENT

The authors would like to express their thanks to all those at Red Bull Technology (for whom the project which led to this paper was undertaken) for their invaluable assistance and insight, and our gratitude for the significant support provided by the EOS group. Also our thanks to Index Instruments for the provision of their REF 804 hand held Refractometer and to IMCD for supply of Silicone Oil used. Thanks also to Joe Nawasra at the University of Warwick Optical Engineering Laboratory for the use of their facilities and advice.

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