Additively Manufactured (3DP) thermite structures vs conventionally manufactured equivalents

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Scope

3DP of thermites

- Background
  - 3D Printing
  - Thermites
  - Why?
  - Current 3DP of thermites
- Methods and Materials
  - Printer
  - Thermites
  - Combustion velocity
- Results and Discussion
  - Manufacturing Times and Density
  - Small scale testing
  - Combustion
- Conclusions
- Further Work
- Summary

Background

Additive Manufacturing - "Process of joining materials to make parts from 3D model data, usually layer upon layer." (ISO/ASTM 52900: 2015)

Forms of Additive Manufacture

- Powder Bed Printing (3DP)
- Fused Deposition Modelling (FDM)
- Electron Beam Welding (EBW)
- Direct Inkjet Writing (DIW)
- Continuous Light Processing (CLIP)

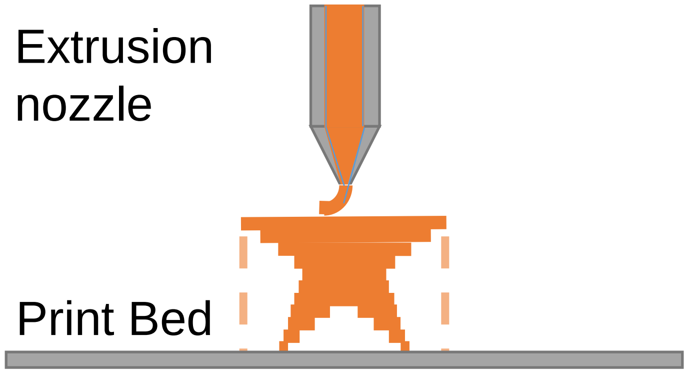


Figure 1. Extrusion based additive manufacturing, FDM.

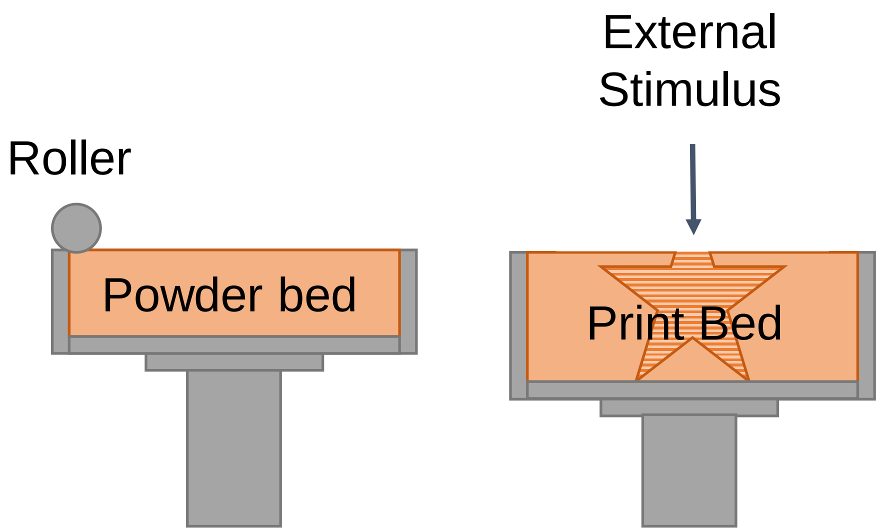


Figure 2. Powder bed based additive manufacturing (3DP)

Background

Thermites

- Metal + Metal Oxide
- Generally gasless and high temperature
- Uses:
    - Welding (railway)
    - Production of ceramics (pipe lining)
    - Purification of metals from ore (uranium)
    - Destruction of equipment

Eigenthum des Kaiserlichen Patentamts.

KAISERLICHES PATENTAMT.

AUSGEGEBEN DEN 4. FEBRUAR 1898.

PATENTSCHRIFT

— № 96317 —

KLASSE 40: HÜTTENWESEN.

FIRMA TH. GOLDSCHMIDT IN ESSEN A. D. RUHR.

Verfahren zur Herstellung von Metallen oder Metalloiden oder Legirungen derselben.

Patentirt im Deutschen Reiche vom 13. März 1895 ab.

Figure 3. Goldschmidt H. 96317: Verfahren zur Herstellung von Metallen oder Metalloiden oder Legierungen derselben. Deutschen: Kaiserliches Patentamt; 1895. https://depatisnet.dpma.de/DepatisNet/depatisnet?action=pdf&docid=DE000000096317A

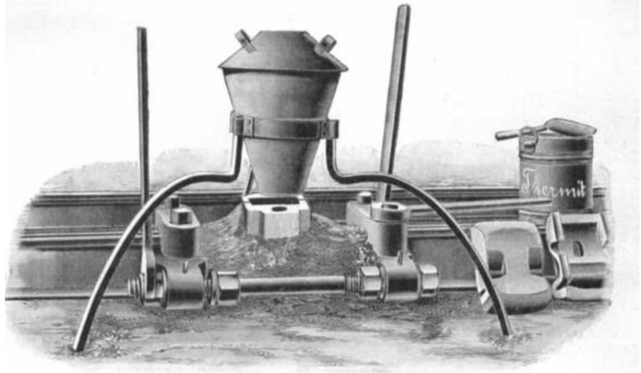


Figure 4. Goldschmidt H. ALUMINOTHERMISCHES SCHWEISSVERFAHREN MIT HILFE EINES AUTOMATISCH WIRKENDEN ABSTICHES. Zeitschrift für Elektrochemie. 1901; 7(68): 935–943.

$$2\,Al + Fe_2O_3 \rightarrow Al_2O_3 + 2\,Fe$$

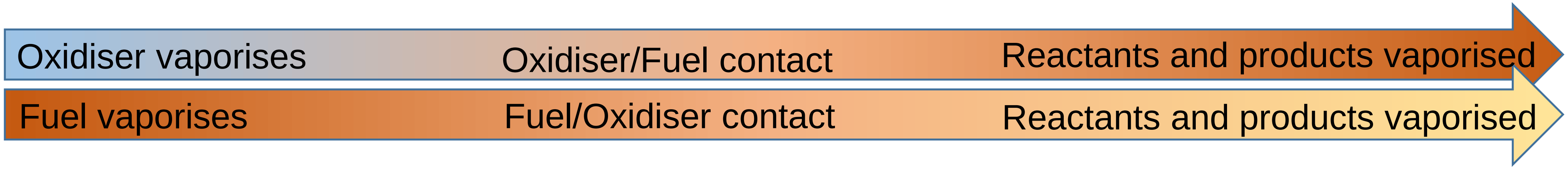
Background

Thermites

- Large range of velocities:

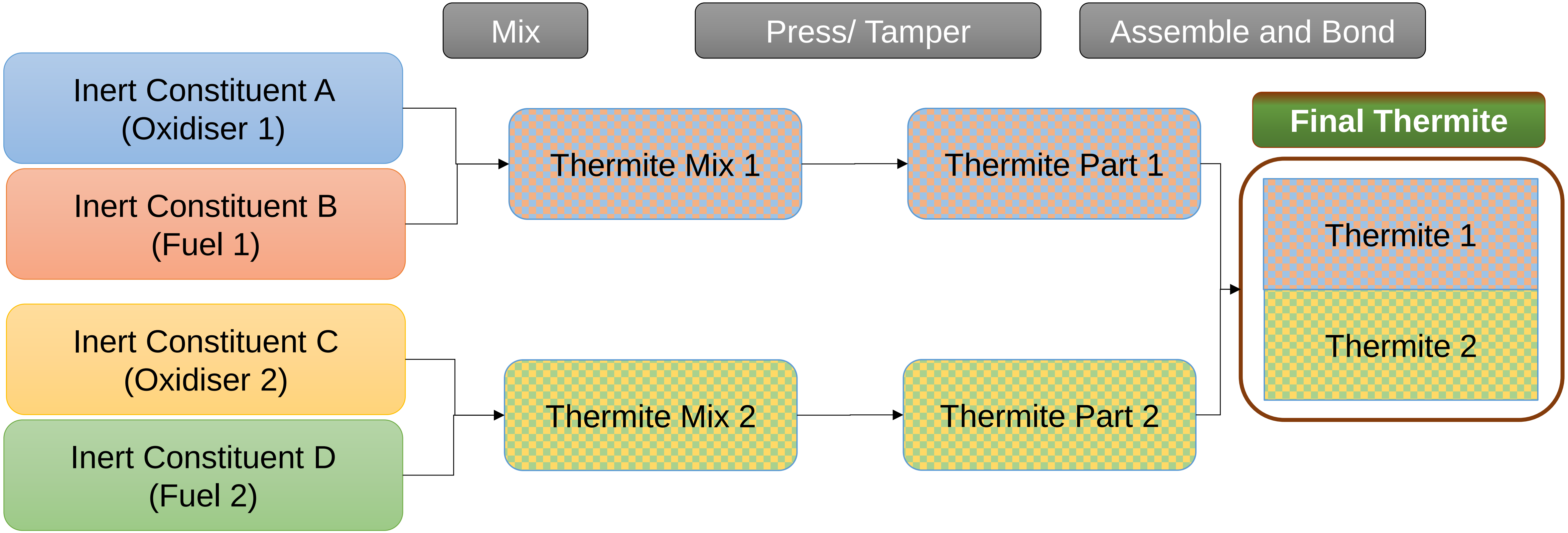
- Wide range of temperatures:

- Different combustion mechanisms:



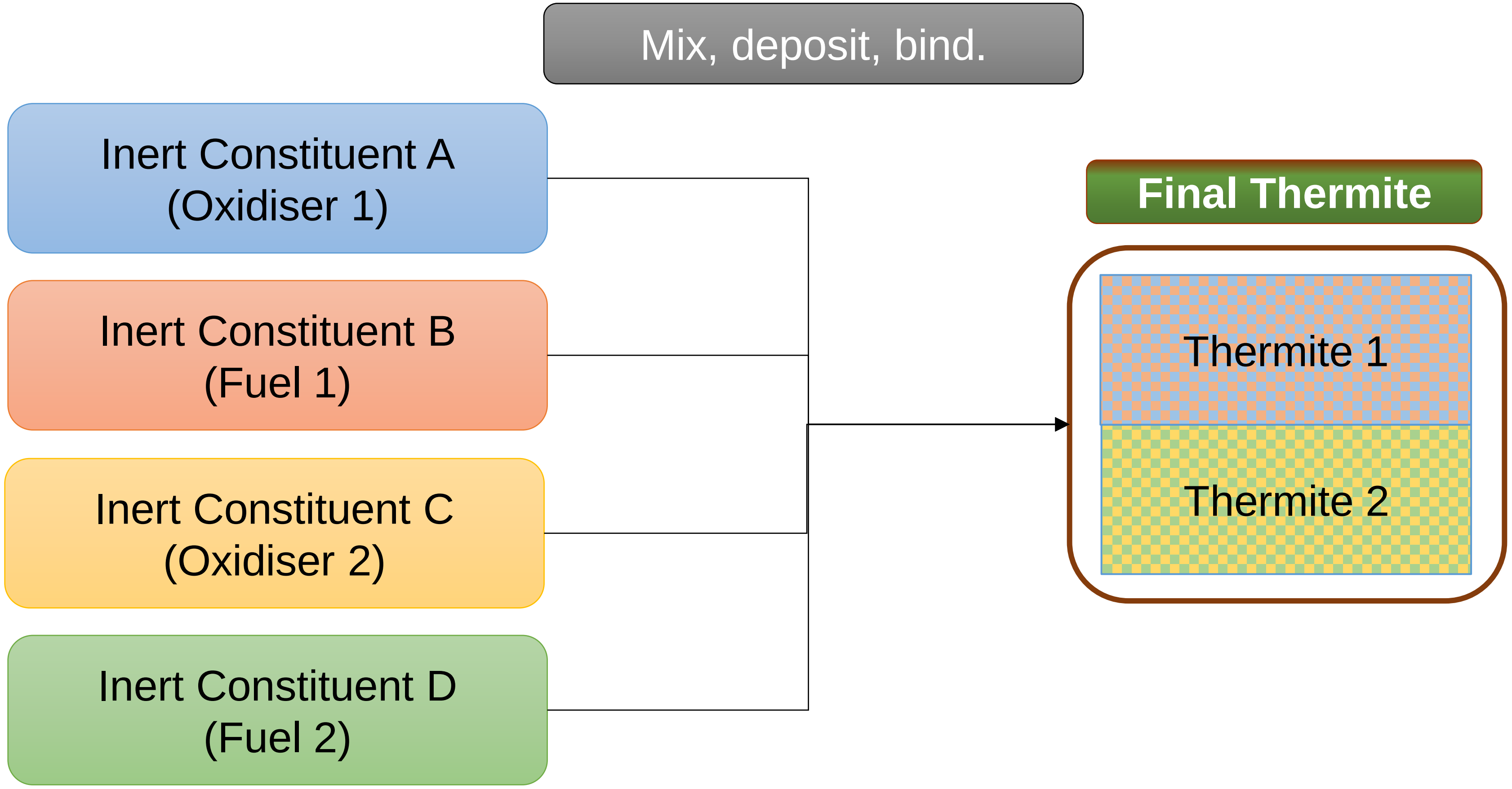
Background

Why? – Conventional Manufacture



Background

Why? – Additive Manufacture



Background

Current thermite additive manufacture

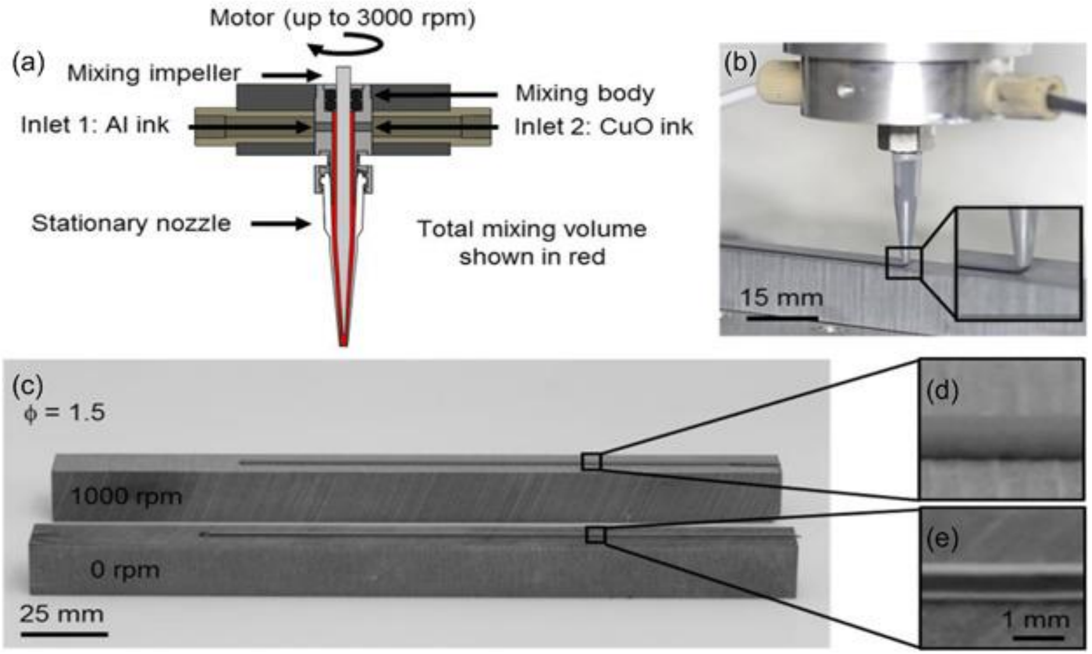


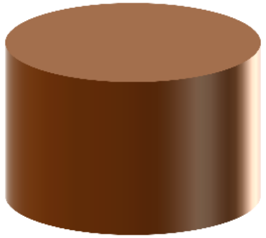
Figure 5. Golobic AM., Durban MD., Fisher SE., Grapes MD., Ortega JM., Spadaccini CM., et al. Active Mixing of Reactive Materials for 3D Printing. Advanced Engineering Materials. John Wiley & Sons, Ltd; 15 May 2019; : 1900147. Available at: DOI:10.1002/adem.201900147

- Predominantly by DIW printing
  - Mixing on printer is possible
  - Limited formulations
  - Focused on nanothermites
- Some evidence of FDM printing
  - Requires more pre-processing than DIW
- Both require formulation of an ink or filament prior to printing.

Materials and Methods

The Printer - Versatility

Figure 6. Cylindrical part, self supporting structure.



Self Supported Structures

- Extrusion like printing
- Powder deposited onto the bed
- Binder is deposited onto powder layer

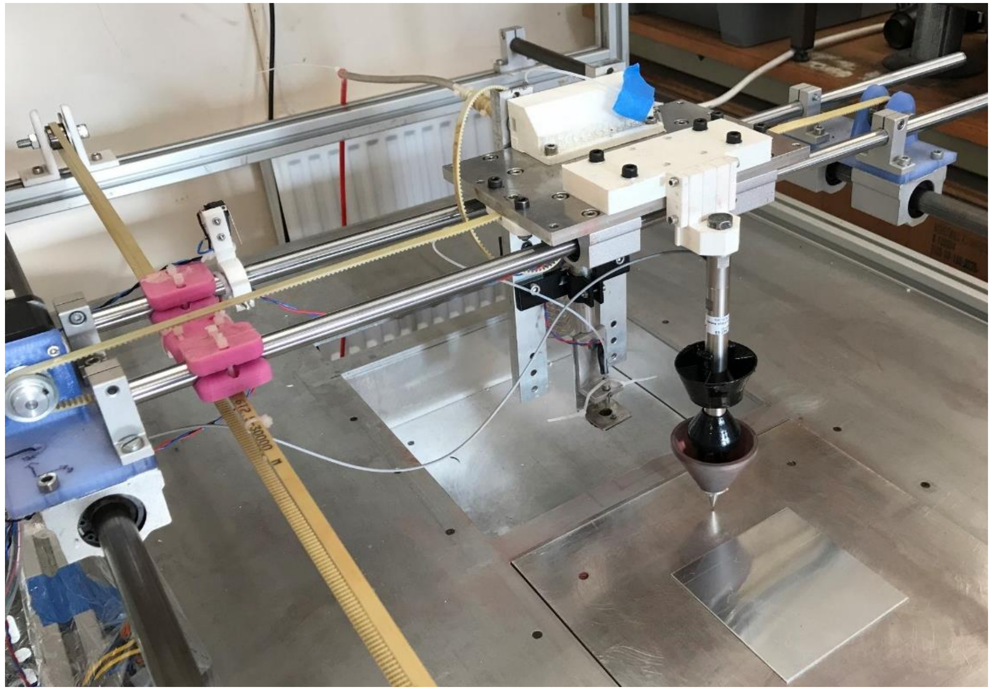


Figure 7. Multi material printer set up for single powder extrusion like printing.

Figure 8. Spherical part, non self supporting structure.

Non Self Supported Structures

- Powder Bed type printing
- Negative shape on print bed filled with powder
- Binder is deposited onto powder only

Materials and Methods

Thermite – Aluminium Fuel

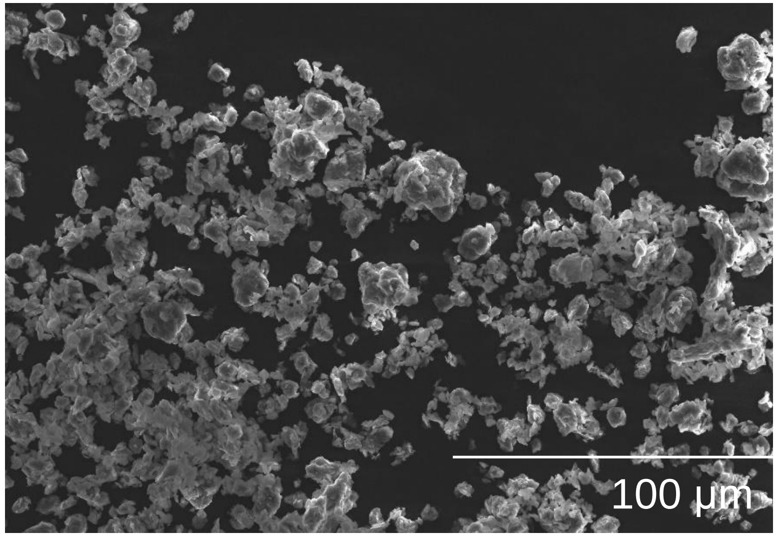


Figure 9. Pyrotechnic aluminum measured average particle size 17 µm. 15.00kV accelerating voltage, x500 magnification.

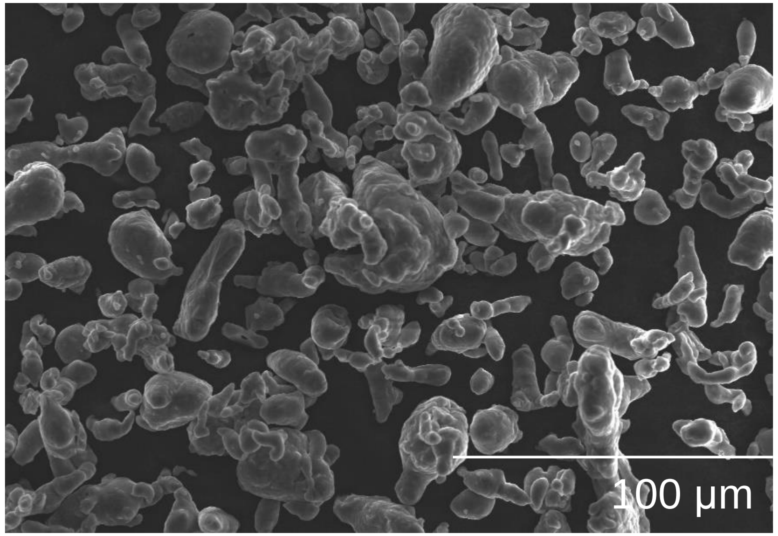


Figure 10. Milled aluminum measured average particle size 25 µm. 15.00kV accelerating voltage, x500 magnification.

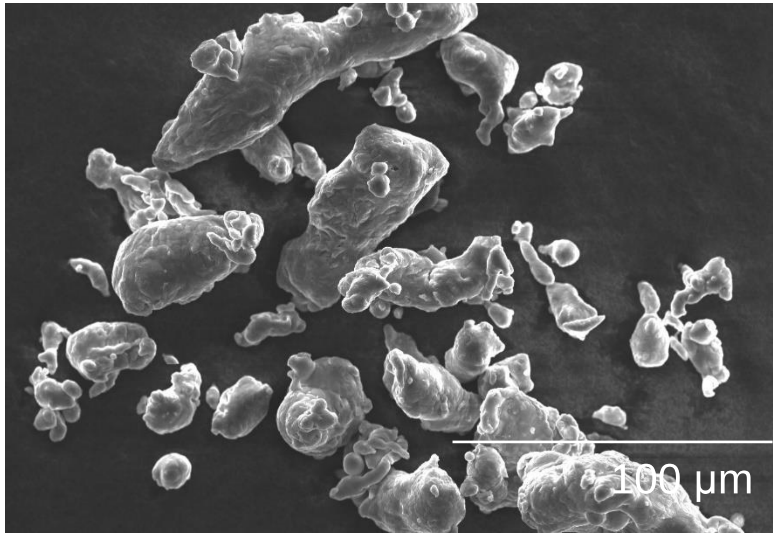


Figure 11. Milled aluminum measured average particle size 42 µm. 15.00kV accelerating voltage, x500 magnification.

Materials and Methods

Thermite – Aluminium Fuel

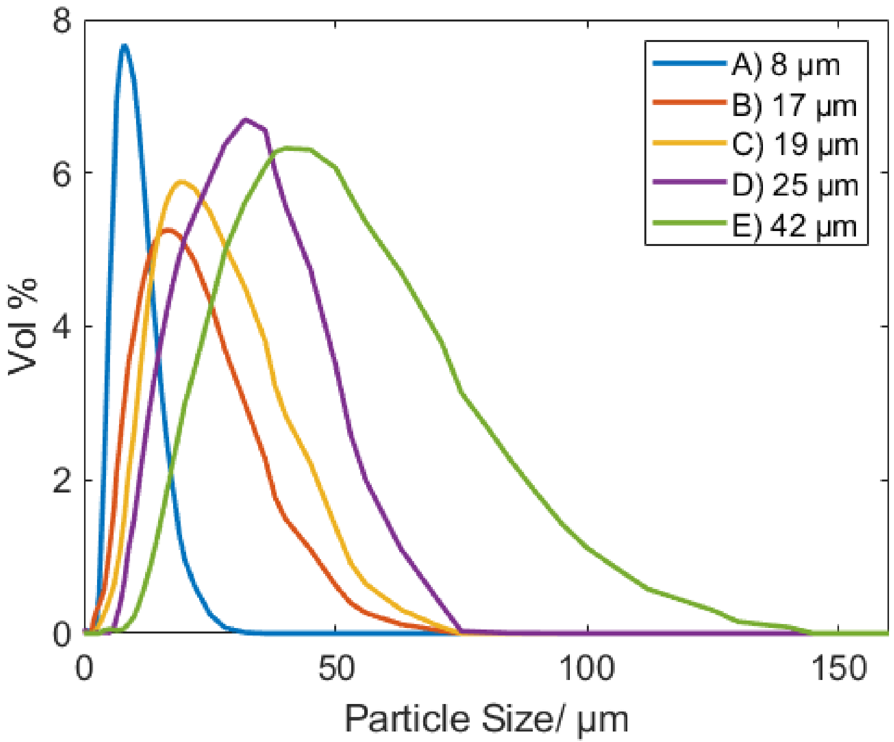


Figure 12. Particle size distributions for the various aluminum samples. Average particle size listed in legend.

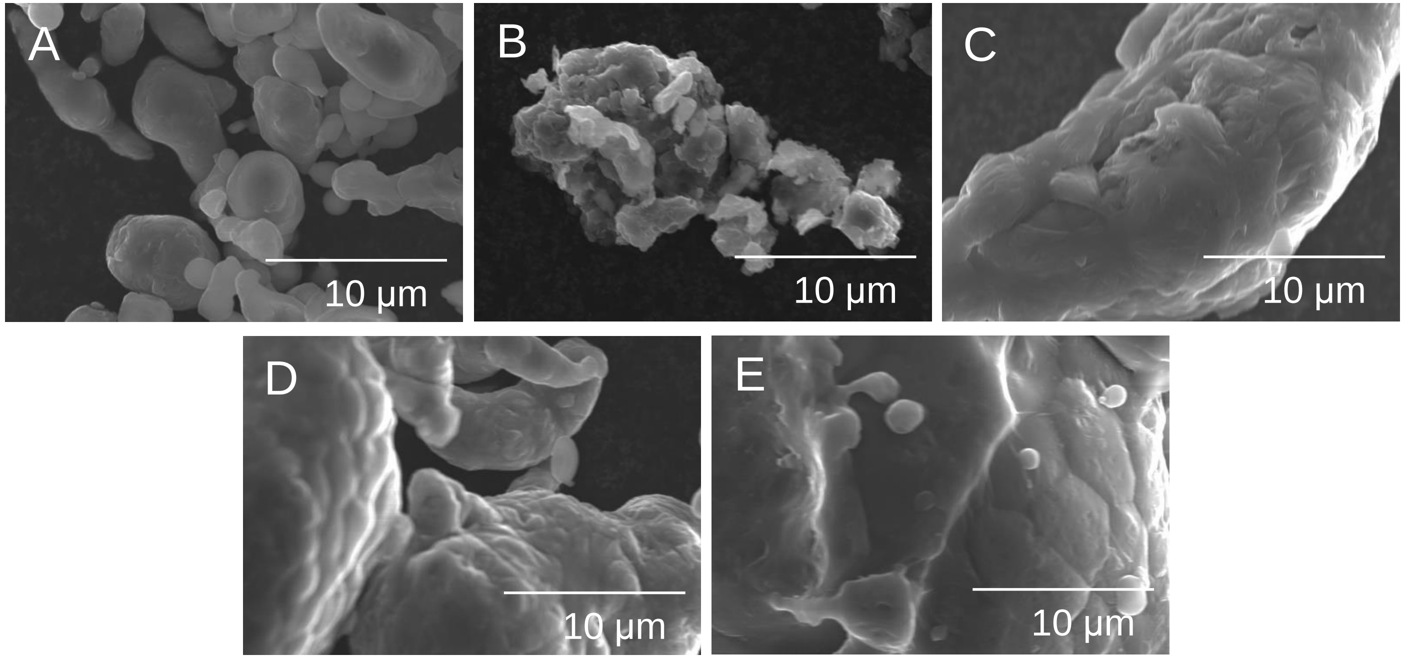


Figure 13. A) Milled aluminium 8 μm B) pyrotechnic aluminum 17 μm C) milled aluminium 19 μm, D) milled aluminium 25 μm, E) milled aluminium 42 μm. 15.00kV accelerating voltage, x3500 – x5500 magnification.

Materials and Methods

Burn tube and thermite manufacture

Figure 14. Photograph of an assembled burn tube. Tube has a 5 or 7 mm internal diameter and 100 mm in length. 6 ports are drilled into the tube that are 10 mm apart, fibre optics are fitted into the holes and secured with a 5 minute cure two part epoxy.

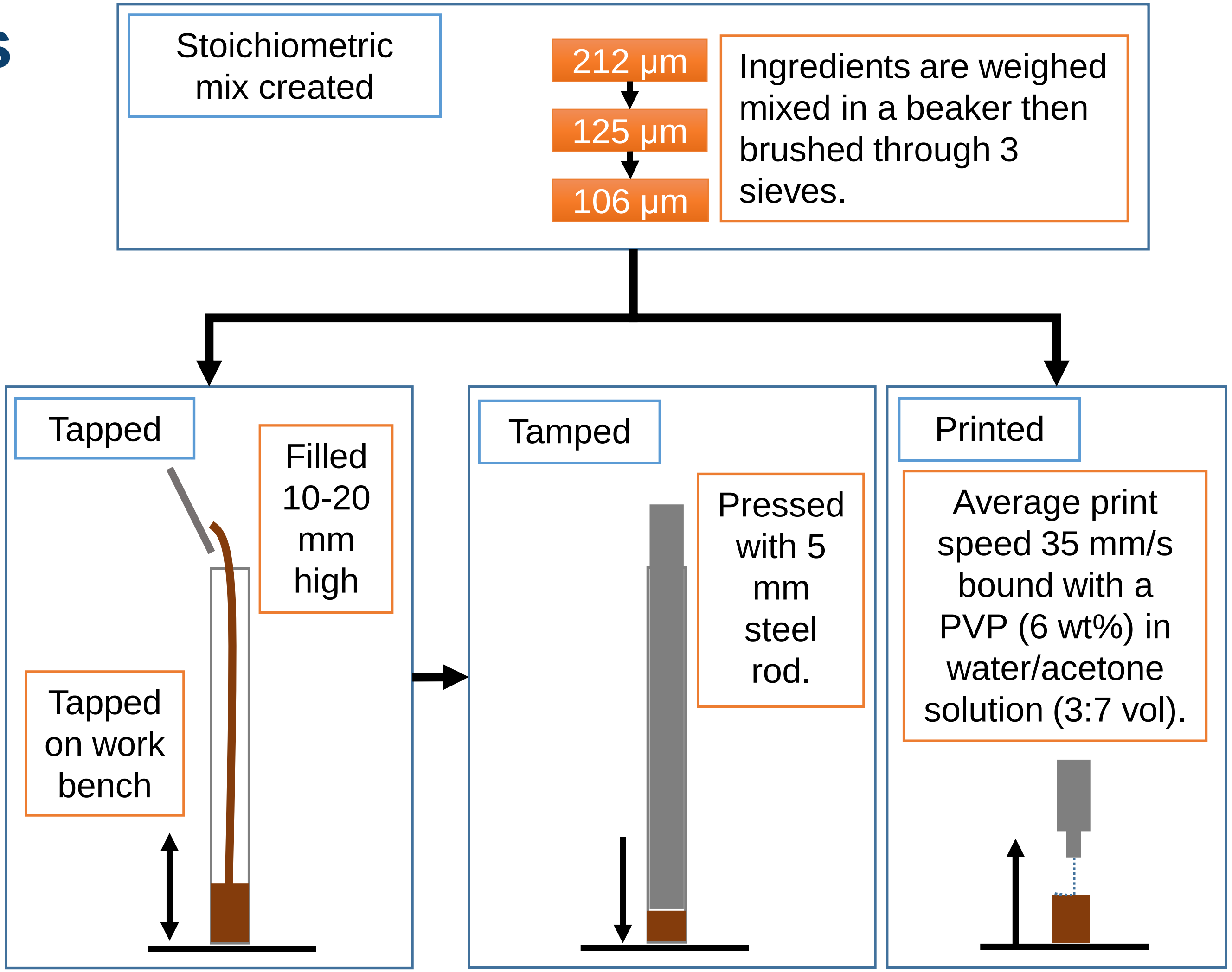


Figure 15. Description of the different part manufacture methods, first a stoichiometric mix of the thermite is made, it is then either tapped or printed. Tamped parts are produced by tapping followed pressing down with a rod

Materials and Methods

Burn Tubes

- Set-up
  - Tubes are assembled vertically
  - An electric match is fitted to the top of the tube
  - An electric trigger switch is used to ignite the electric match and trigger recording on the oscilloscope

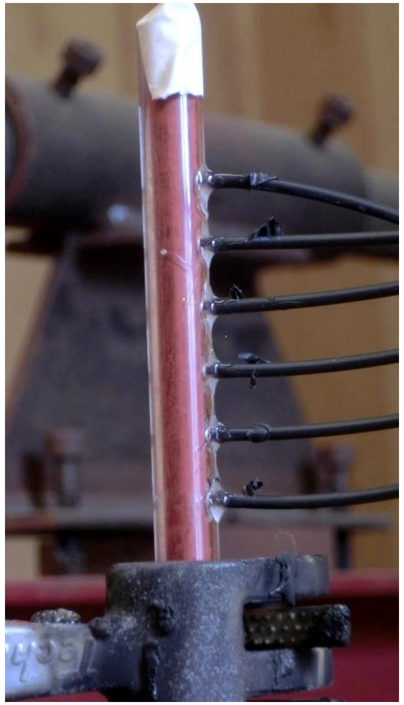


Figure 16. Burn tube set-up

- Data Collection
  - Combustion is recorded using the oscilloscope and a high speed camera
  - Residues were collected from a terracotta plate beneath each shot
  - The time at which light is first detected on each fibre optic, for simplicity, is considered to be the flame front.

Materials and Methods

Printed Specimens

- Print parameter optimisation is ongoing
- Specimens used for combustion comparison demonstrate curvature after printing (deformation)
- Volumes are calculated assuming that the curved cylinder is a segment of a toroid (doughnut)
    - 5 measures of each dimension
        - Height in z
        - Width in x
        - 2 lengths in y (y_1, y_2)

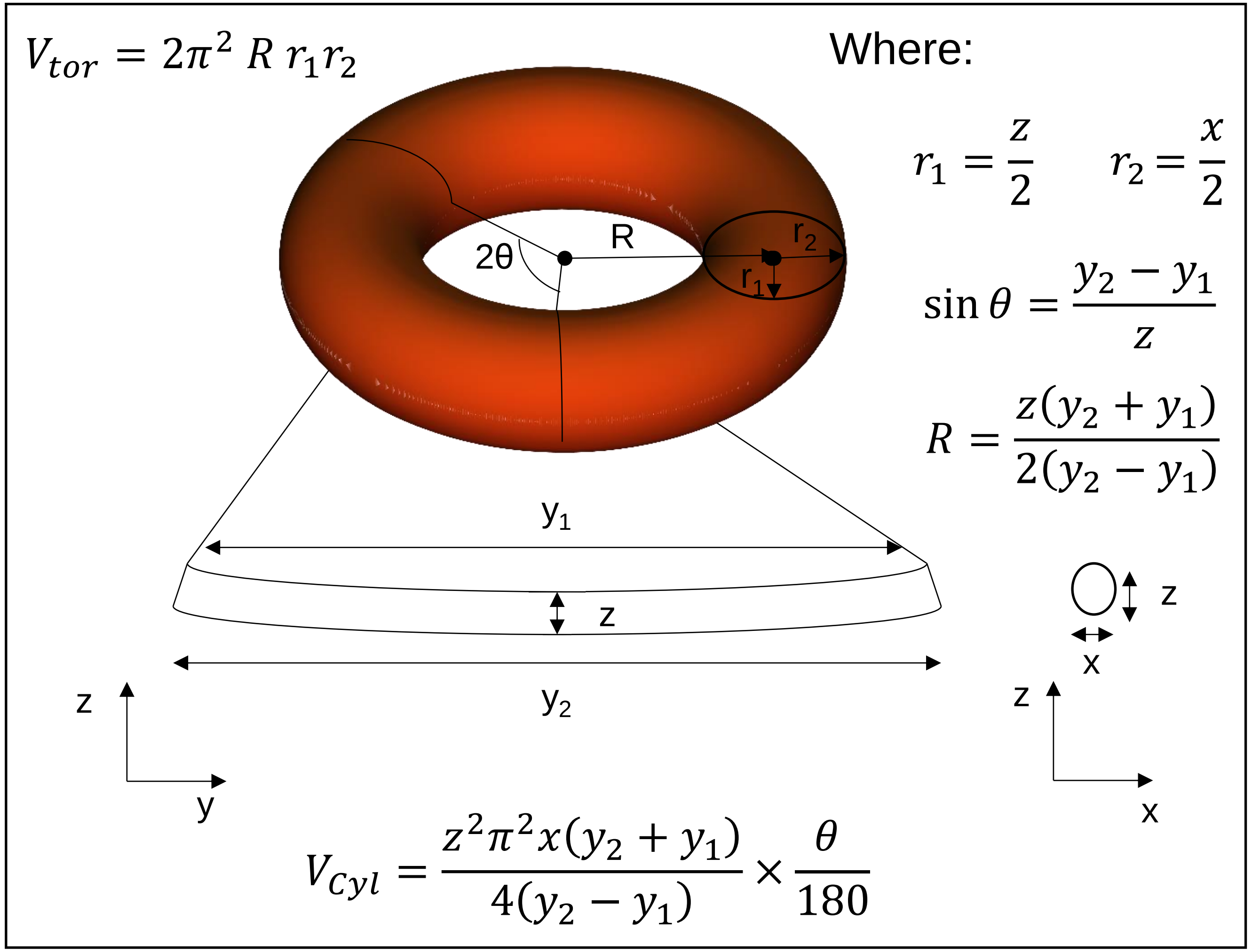


Figure 17. Graphical description of the volume calculation for curved cylinders.

Results and Discussion

Manufacturing times and density

Table 1. Human resource, production times and resultant variations in density per production method.

Type of manufacture	Human resource/ mins	Production time/ mins	Coefficient of Variation/ %
Tapped	5	5	13
Tamped	20	20	12
Printed	5	50	7

- Coefficient of variation when printing the thermite is decreased compared to the tapped or tamped parts

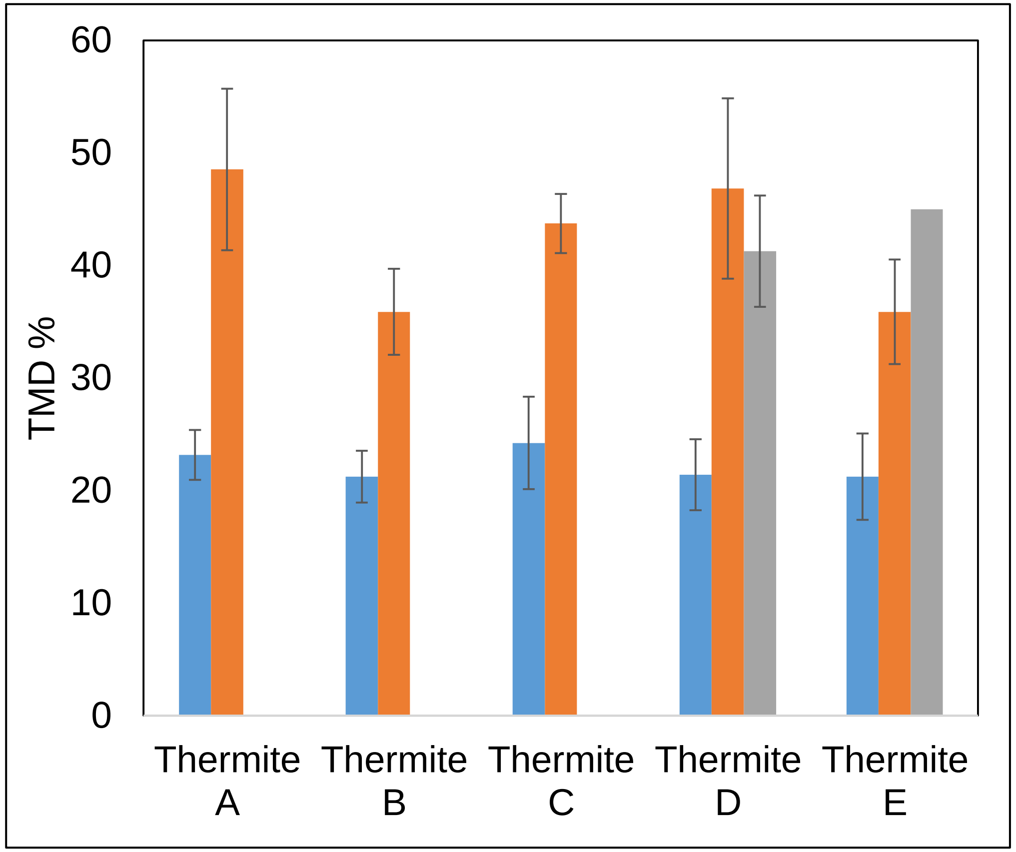


Figure 18. Chart displaying the average theoretical maximum densities (TMD) obtained for each thermite in each production process. Tapped (blue), Tamped (Orange) and Printed (Grey). Error Bars are the standard deviation of the data set.

Results and Discussion

Small scale testing – DSC/TGA

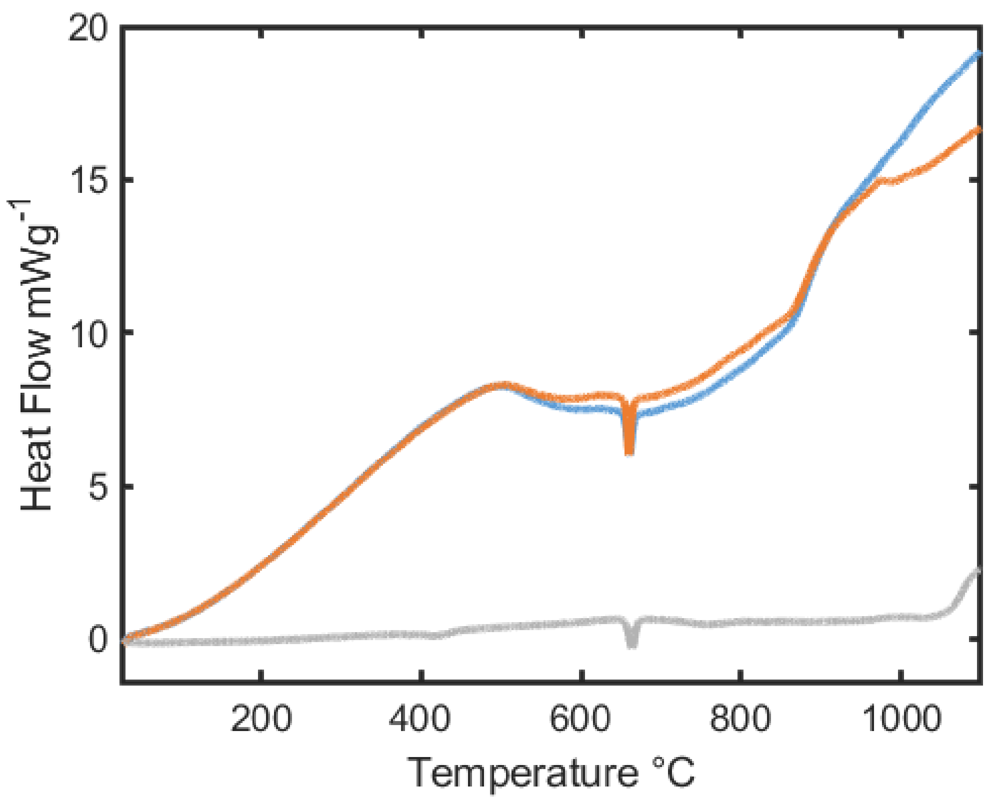


Figure 19. Heat flow of tapped (blue), tamped (orange) and printed (grey) Thermite D. Heating from 25 – 1100 °C at 10 °C min^{-1}.

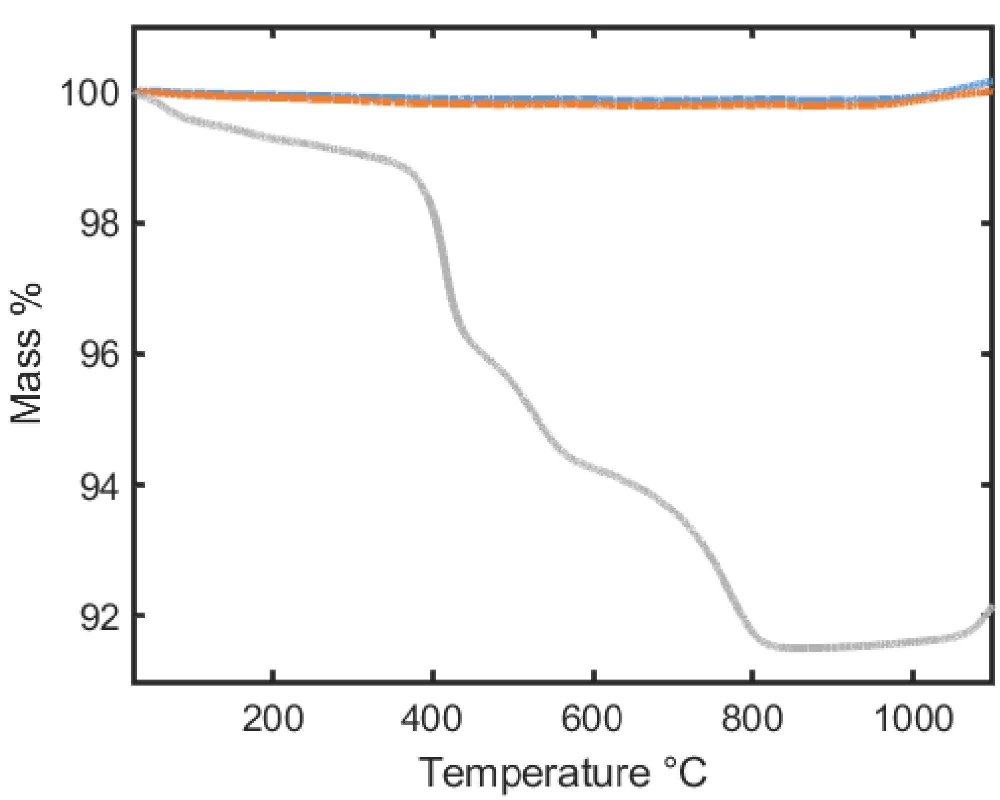


Figure 20. Mass change of tapped (blue), tamped (orange) and printed (grey) Thermite D. Heating from 25 – 1100 °C at 10 °C min^{-1}.

Results and Discussion

Combustion testing

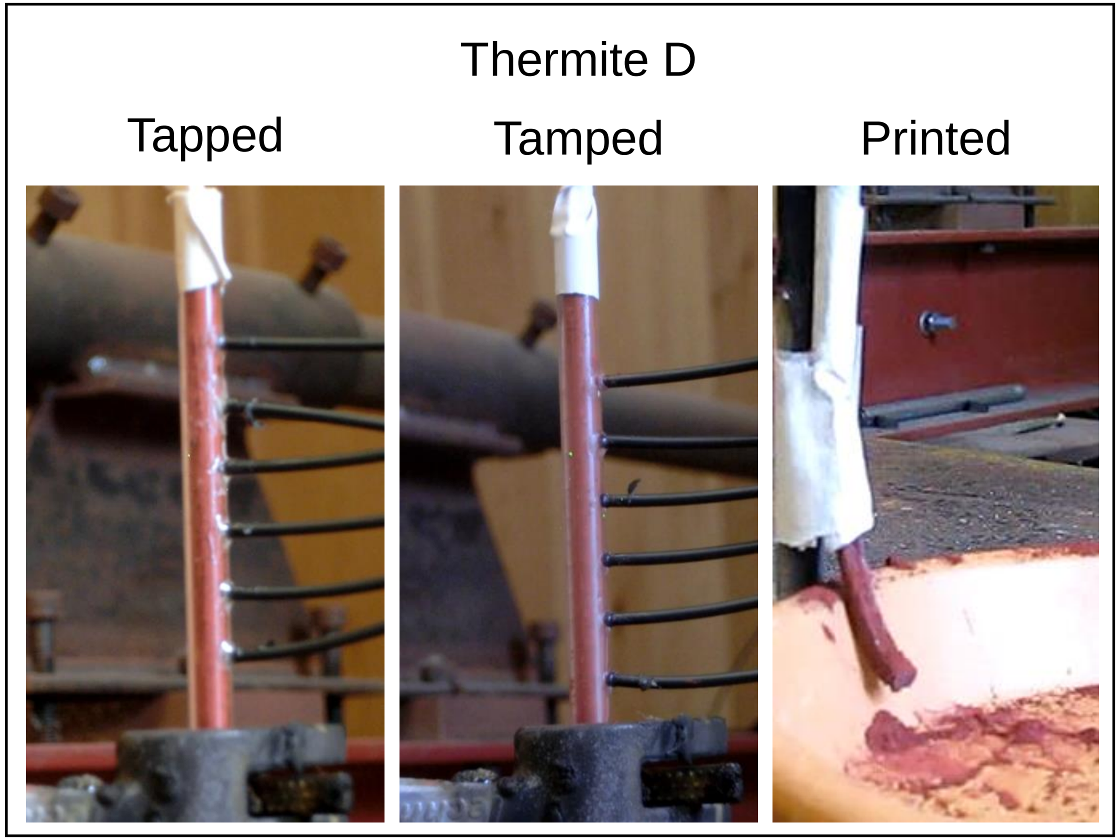


Figure 21. Tapped, tamped and printed Thermite D, average combustion velocities measured at 19.0, 33.3 and 7.9 mms^{-1} respectively**.**

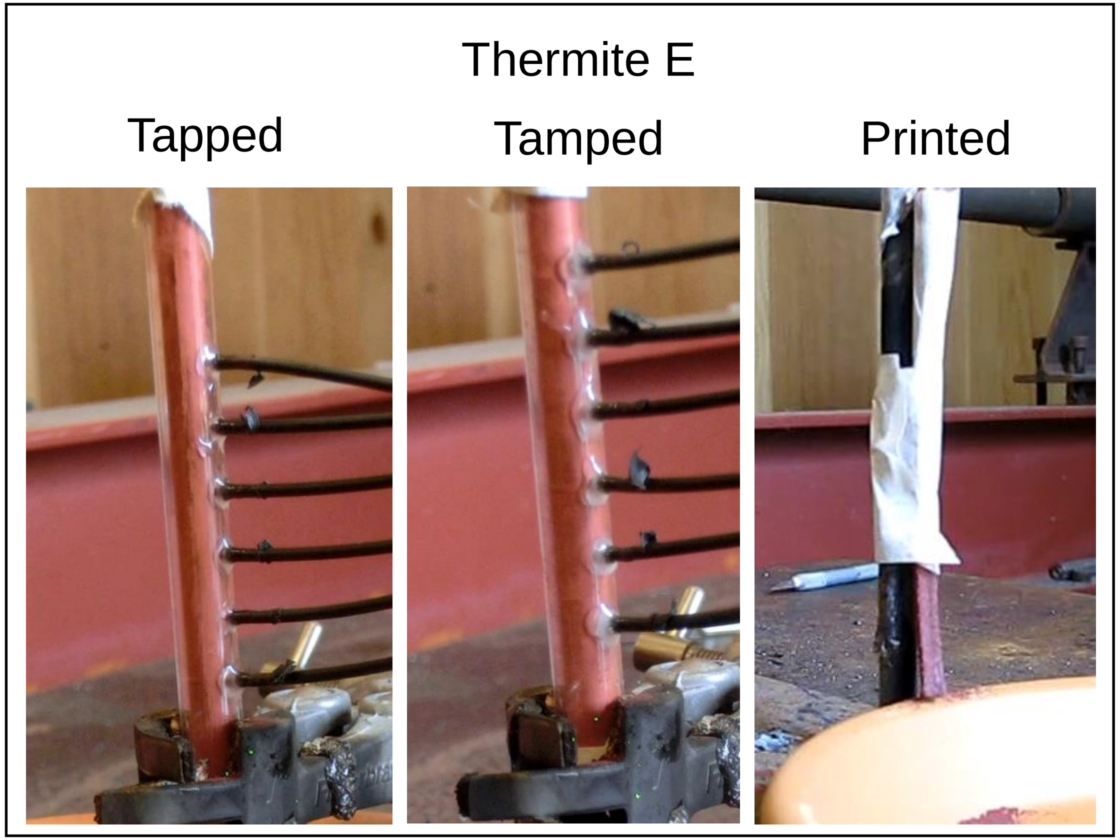


Figure 22. Tapped, tamped and printed Thermite E, average combustion velocities measured at 14.0, 24.6 and at 7.5 mms^{-1} respectively**.**

Conclusions

Somewhere in between loose packed and pressed

Figure 23. Printed thermite disc.

- Final part density for printed parts across the thermites being testing is inconclusive, but does indicate that the density is likely to be somewhere around that of Tamped materials
- Indications that reproducibility in density during manufacture is increased when dry printing

Figure 24. Printed thermite cylinder.

- Small scale testing shows that the binder reduces heat flow in the thermite and that the binder is burned off before reaction of the metal and metal oxide
- Combustion speeds were difficult to determine using the available printed parts, due to deformation
  - Parts did not fragment and burnt the length demonstrating that this is a viable method for thermite manufacture

Future Work

Harder, Faster, Hotter

- Mechanical properties of printed parts
- Speed modifications through architecture and gradients
- Heat of combustion calculations
- Measurement of the heat of combustion
- Ignition speeds and temperatures

Figure 25. Burn tube, toward end of test.

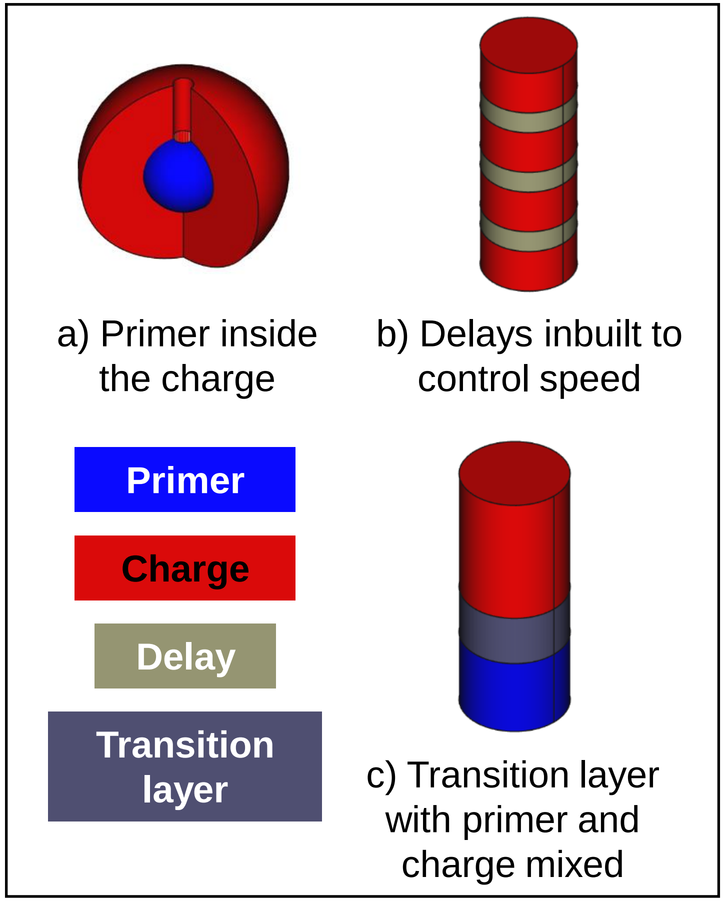


Figure 26. Options for architecture and gradient changes.

Summary

3DP of Thermites

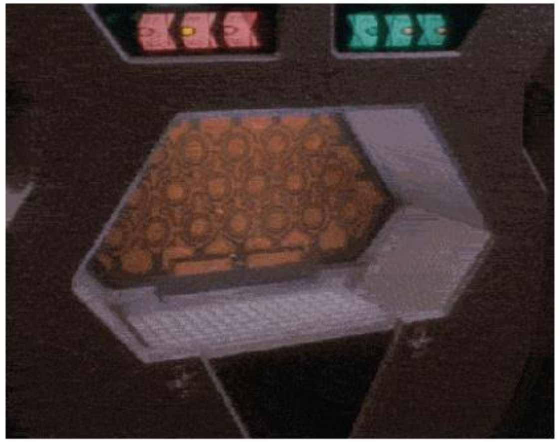
- Background
  - 3D Printing
  - Thermites
  - Why?
  - Current 3DP of thermites
- Methods and Materials
  - Printer
  - Thermites
  - Burn Tubes
- Results and Discussion
  - Manufacturing Times and Density
  - Small scale testing
  - Combustion
- Conclusions
- Future Work

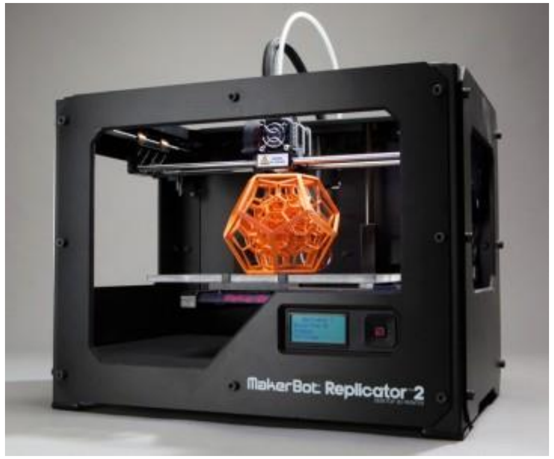
Special Thanks

To

- Supervisor: Dr Ranko Vrcelj
- Colleague: Jacopo Bonifacio
- Sponsors: [dstl]
- The guys from the Centre for Defence Chemistry’s, Explosives Science Group, Vulnerability Group
    - Dr Chris Stennett
    - Jim Clements
    - Matt Goldsmith
    - Scott Clews

  (Without whom I’d be lost!)





Thank you for listening

I will now take questions

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Additional Information

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FO vs Video

Comparison of FO and Video methods for combustion velocity