

From Waste Steel to Matériel: Additive Manufacturing Enabled Agile Manufacturing

WP18-1176

Diran Apelian
Worcester Polytechnic Institute

August, 2023



REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY) 30/08/2023		2. REPORT TYPE SERDP Project Outbrief		3. DATES COVERED (From - To) 6/4/2018 - 6/4/2023	
4. TITLE AND SUBTITLE From Waste Steel to Matériel: Additive Manufacturing Enabled Agile Manufacturing				5a. CONTRACT NUMBER 16-C-0020	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Diran Apelian Jianyu Liang Worcester Polytechnic Institute Brandon McWilliams Army Research Laboratory				5d. PROJECT NUMBER WP18-1176	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Worcester Polytechnic Institute Washburn Labs 329 100 Institute Road Worcester, WA 01609				8. PERFORMING ORGANIZATION REPORT NUMBER WP18-1176	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Strategic Environmental Research and Development Program (SERDP) 4800 Mark Center Drive, Suite 16F16 Alexandria, VA 22350-3605				10. SPONSOR/MONITOR'S ACRONYM(S) SERDP	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) WP18-1176	
12. DISTRIBUTION/AVAILABILITY STATEMENT DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT The project address the FY 2018 SERDP Statement of Need #WPSON-18-C4 that aims to demonstrate that waste streams generated at FOBs and battlefield scrap can be repurposed using field-capable manufacturing processes to produce replacement parts or repair equipment in the field. The Technical Objectives of this project are listed below: 1. Creating an effective sorting, chemical composition monitoring and composition adjustment process for iron wastes at FOBs that enables quality control of material. 2. Establishing additive manufacturing (AM) technology enabled investment casting (IC) using iron wastes from FOBs as the cast material. 3. Optimizing and minimizing post process treatments for required quality of cast parts.					
15. SUBJECT TERMS Second Order Rate Constants, Reactive Reductant Concentrations, Limited Reductant Kinetic Experiments, Waste Steel, Additive Manufacturing, Agile Manufacturing					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UNCLASS	18. NUMBER OF PAGES 40	19a. NAME OF RESPONSIBLE PERSON Diran Apelian
a. REPORT UNCLASS	b. ABSTRACT UNCLASS	c. THIS PAGE UNCLASS			19b. TELEPHONE NUMBER (Include area code) 508-831-5992

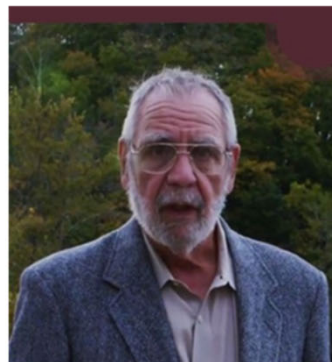
Project Team



Drs. Diran Apelian, Jianyu Liang, Rick Sisson and Brajendra Mishra



Drs. Brandon McWilliams
and Jian Yu

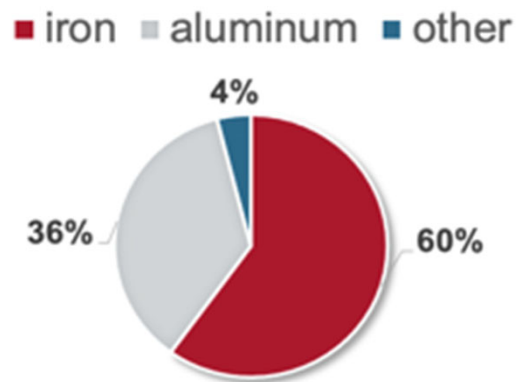


Mr. Robert De Saro



Background

- The project started in FY2018.
- The project address the FY 2018 SERDP Statement of Need #WPSON-18-C4 that aims to demonstrate that waste streams generated at FOBs and battlefield scrap can be repurposed using field-capable manufacturing processes to produce replacement parts or repair equipment in the field.
- Ferrous (iron) waste makes up the **largest** category of metals in solid waste at Forward Operating Bases (FOBs).
- Currently, the disposal of solid waste is very dependent on the duration of a campsite, the current security situation of a particular site, and the ability and willingness of local infrastructure to handle these wastes.
- Need to develop a manufacturing processes and enable the fabrication of **replacement parts** or **repair operation** in the field.



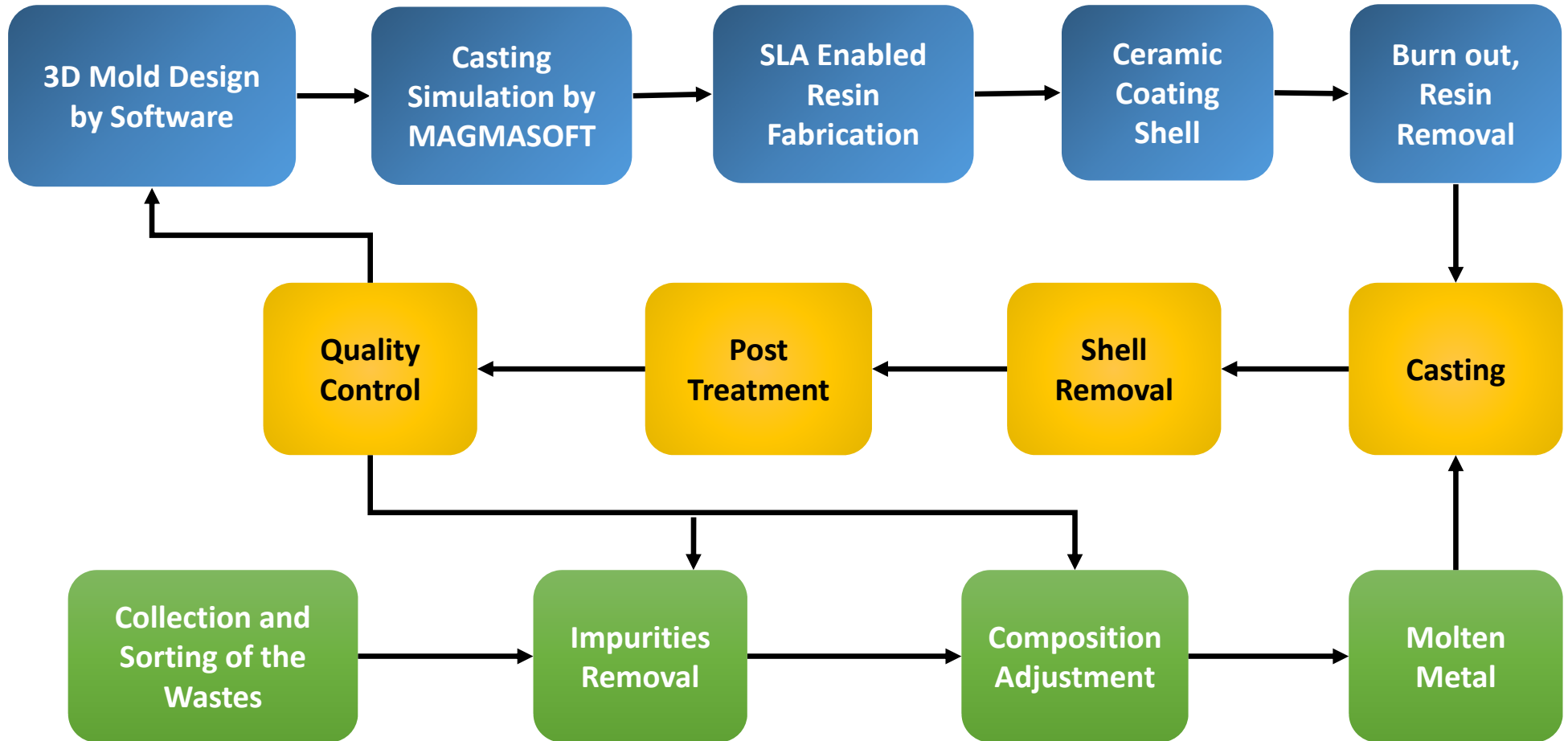
Recommended breakdown of metal waste recipe at FOBs.



Technical Objectives

1. Creating an effective sorting, chemical composition monitoring and composition adjustment process for iron wastes at FOBs that enables quality control of material
2. Establishing additive manufacturing (AM) technology enabled investment casting (IC) using iron wastes from FOBs as the cast material
3. Optimizing and minimizing post process treatments for required quality of cast parts

Technical Approach







Schematic of the proposed manufacturing process for ferrous wastes.

Results

Waste Metal Characterization







- 2,567.00 lb. of Waste Metal Received from ARL.
- Portable OES (Hitachi High-Tech PMI Master UV Touch) was selected to characterize waste metal chemical composition.
- Established a waste metal database. Visual and dimensional information, as well as chemical composition were recorded.

Waste Metal Database

Metal Waste	Part Description	Weight (lb.)	Dimensions (inch)	Alloy Recognition
	Plate with partial rust and painted coating	4.02	9.00" x 8.50" x 2.25"	4340
	Block entirely covered in rust	15.69	6.00" x 6.00" x 5.75"	Non-Specified
	Brake Rotor entirely covered in rust	11.98	10.00" x 2.00"	Carbon Steel
	Small Round Stock partially covered in rust	0.28 (per piece)	1.125" x 2.00"	12L14



Waste Metal Database

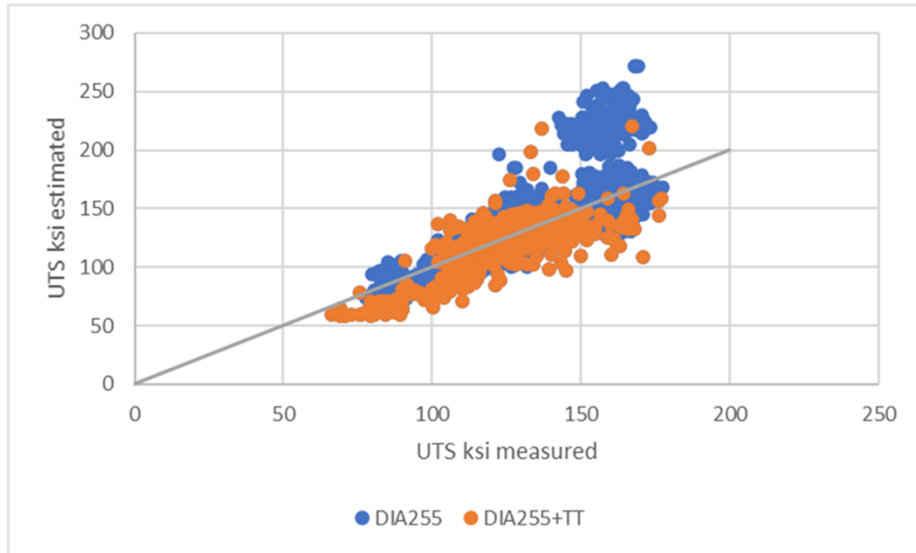
Picture of Scrap	Categorization	Dimensions (Approximate, Overall Size)	Contamination	Weight (lbs.)	Grade	Fe(%)	C(%)	Si(%)	Mn(%)	Cr(%)	Mo(%)	Ni(%)	Al(%)	Co(%)	Cu(%)
	Hydraulic	27" x 10"	Coating, Partial, Plastic Comp, Hydraulic Fuel	14.14	1005-AISI	99.5	0.0551	0.012	0.188	0.0398	<0.003	<0.005	0.0357	0.002	0.0201
	Exhaust Pipe	22" x 6"	Partial Rust	6.49	1005-AISI	99.5	0.0616	<0.005	0.273	/	<0.005	<0.005	0.0294	0.0061	0.03
	Tank	20" x 10" x 6"	Partial Rust, Coating, Plastic Comp.	6.17	1005-AISI	99.2	0.0887	0.0117	0.513	0.0378	<0.003	0.0119	0.0373	0.0029	0.0357
	Conduit Box	18.75" x 13.5" x 4.75"	Coating, Partial Rust, Internal Components	15.47	1005-AISI	99.6	0.0619	<0.005	0.178	0.0122	<0.003	0.0069	0.0186	0.0041	0.0112
	50 Gallon Drum Lid	23.5" x 1"	Entirely Covered in Rust	6.18	1005-AISI	99.5	0.0698	0.0095	0.224	0.0326	0.0032	0.0073	0.0414	0.0027	0.0441
	Hollow Square Tube	8 x 4 1/8 x 8 3/8	Partial Rust	6.03	1005-AISI	98.7	0.248	0.0064	0.818	0.0136	<0.003	<0.005	0.042	0.0035	0.0181

Chemical Composition Adjustment

- Created a blending model for heat calculation and composition adjustment

Steel 1 Carbon Steel																		
		CE	DI	% C	% Si	% Mn	% P	% S	% Cr	% Mo	% Ni	%Al	%Co	%Cu	%V	%Sn		
Recovery				0.9	0.95	0.95	1.0	1.0	0.97	0.99	0.99	1.0	1.0	1.0	1.0	1.0		
Target	Min.	0.23	0.27	0.15	0.40	0.50	0	0	0	0	0	/	/	/	/	/		
	Max.	0.67	4.25	0.30	0.60	1.20	0.035	0.035	0.50	0.20	0.50	/	/	/	/	/		
Heat Composition		0.35	0.69	0.147	0.506	0.768	0.021	0.013	0.190	0.054	0.343	0.015	0.005	0.180	0.009	0.011		
Heat Size (lb.)		70																
Waste Parts	Name	Remain	Added (lb.)	Fraction	Dimensions	% C	% Si	% Mn	% P	% S	% Cr	% Mo	% Ni	%Al	%Co	%Cu	%V	%Sn
#3-35	Plate with Square Hole	45.400	54.600	0.780	27.75" x 15.125" x 1.0"	0.136	0.050	0.809	0.017	0.008	0.077	0.014	0.084	0.019	0.003	0.188	0.001	0.009
#4-15	Big Thread Barrel 5	32.780	10.000	0.143	4.5" x 24"	0.355	0.320	0.739	0.055	0.022	0.879	0.284	1.870	0.002	0.017	0.090	0.052	0.020
#3-32	Big L Beam	27.810	5.000	0.071	3.0" x 3.0" x 64.0"	0.087	0.270	0.972	0.002	0.048	0.123	0.037	0.189	0.001	0.009	0.284	0.022	0.015

Using Critical Diameter



Source	Date Proposed	Published Formula	Notes
Grossman ^{28,30}	1942	$DI_g = f(N_A) * f_C * f_{Si} * f_{Mn} * f_P * f_S * f_{Cu} * f_{Ni} * f_{Cr} * f_{Mo}$	Calculate hardenability
Holloman & Jaffe ⁴³	1945	$DI_{HJ} = f(N_A) * C^{1/2} * (1 + 0.64 * Si) * (1 + 4.10 * Mn) * (1 + 2.83 * P) * (1 - 0.62 * S) * (1 + 0.27 * Cu) * (1 + 0.52 * Ni) * (1 + 3.33 * Cr) * (1 + 3.14 * Mo) * f_B$	
ASTM A255 ³⁶		$DI_{A255} = 0.54 * C * (1 + 3.333 * Mn) * (1 + 0.7 * Si) * (1 + 0.33 * Ni + 0.066 * Ni^2 - 0.55 * Ni^3 + 0.18 * Ni^4) * (1 + 2.16 * Cr) * (1 + 3 * Mo) * (1 + 0.365 * Cu) * (1 + 1.73 * V)$	
Ho ⁴⁴	1976	$DI_{C7}^2 = 0.9551 * C$	DI base N=7
Ho ⁴⁴	1976	$DI_{C8}^2 = 0.8240 * C$	DI base N=8
Ho ⁴⁴	1976	$DI_H = (0.8240 * C)^{1/2} * (1 + 0.2211 * Si + 0.1280 * Si^2) * (1 + 0.2353 * Mn + 0.5698 * Mn^2) * (1 + 1.634 * Cr + 0.0270 * Cr^2) * (1 + 0.7671 * Ni + 0.1229 * Ni^2) * (1 + 1.572 * Mo + 0.5893 * Mo^2) * (1 + 1.176 * Cu + 0.3339 * Cu^2)$	
Dobrzanski & Sitek ^{41,45,46}	1999	$DI_{BDS} = 0.6 * (C)^{0.5} * \exp(-0.816 * N_A)$	Base DI
Moser & Legat ⁴¹	1969	$DI_{M\&L} = DI_{BDS} * 3.28^{Mo} * 2.21^{Mn} * 2.13^{Cr} * 1.4^{Si} * 1.47^{Ni}$	Modified version of Grossman
Mostert & Rooyen ⁴¹	1991	$DI_{M\&R} = 46.5 * C^{0.61} * (2.0)^{Mn} * (3.7 * C^{0.43} * (1 + Mo)^{-0.89})^{Cr} * (C^{-0.74})^{Mo} * (1.6 * C^{0.07})^{Ni} * (1.26)^{Si} * 0.95^{N_A}$	For carburizing grades

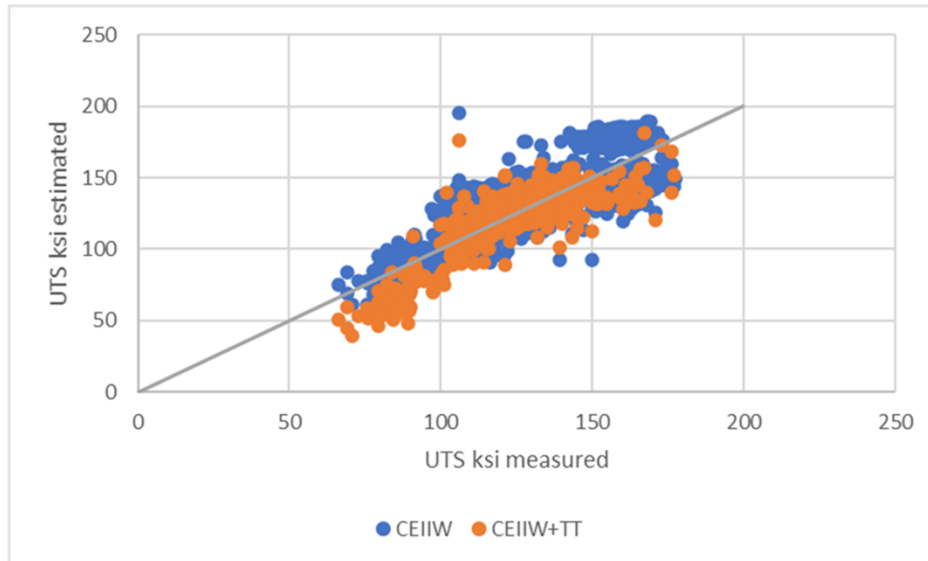
$$DI_{A255} = 0.54 * C * (1 + 3.333 * Mn) * (1 + 0.7 * Si) * (1 + 0.33 * Ni + 0.066 * Ni^2 - 0.55 * Ni^3 + 0.18 * Ni^4) * (1 + 2.16 * Cr) * (1 + 3 * Mo) * (1 + 0.365 * Cu) * (1 + 1.73 * V)$$

$$UTS = 13.17 * DI_{A255} + 73.8 \quad \text{Standard error of 13.13}$$

$$UTS = 13.17 * DI_{A255} + 0.10 * (1130 - T_T) + 73.8$$

Standard error of 11.28 ksi

Using Carbon Equivalent



$$CE_{IIW} = C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15$$

$$UTS = 210.64 * CE_{IIW} - 3.27 \quad \text{Standard error of 11.90 ksi}$$

$$UTS = 210.64 * CE_{IIW} + 0.09 * (1100 - T_T) - 3.27 \quad \text{Standard error of 9.66 ksi}$$

Source	Date Proposed	Published Formula	Notes
BS2642 ²³ British Standard	1958	$CE_{BS} = C + Si/24 + Mn/6 + Cr/5 + Ni/13 + V/5 + Mo/4 + Cu/15$	BS standard for welding medium YS steel BS 968 a
Winterton ^{23,25}	1961	$CE_{Winterton} = C + Mn/6 + Cr/10 + Ni/20 - V/10 - Mo/50 + Cu/40$	Analysis of 12 CE formulas
JWES ^{23,26,48,51}	1973	$CE_{Wes} = C + Si/24 + Mn/6 + Ni/40 + Cr/5 + Mo/4 + V/14$	C-Mn with high CE
IIW ^{23,25,26,48,51}	1967	$CE_{IIW} = C + Mn/6 + (Cu + Ni)/15 + (Cr + Mo + V)/5$	C-Mn with high CE
Ito and Bessyo ^{23,25,26,48,51}	1968	$P_{cm} = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 + V/10 + 5 * B$	C ≤ 0.12 pipeline steels
Lorenz & Duren ^{24-26,51}	1981	$CE_{eq} = C + Si/11 + Mn/8 + Cu/9 + Ni/17 + Mo/6 + V/3$	For estimating HV _b
Proprietary		$CE_{x2} = C + (Mn + Cr)/3 + (Si + Ni)/6 + Mo/2$	C-Mn with higher C
Yurioka et al. ²⁴	1983	$CE_N = C + (0.75 + 0.25 * \arctan(20 * (C - 0.12))) * (Si/24 + Mn/6 + Cu/15 + Ni/20 + (Cr + Mo + Nb + V)/5 + 5 * B)$	Modified to have interaction of alloys with C
Yurioka et al. ⁵⁴	1987	$CE_{my} = C + Si/24 + Mn/6 + Cu/15 + Ni/12 + Mo/4 + Cr/8 + \Delta H$	For martensite
Yurioka et al. ⁵⁴	1987	$\Delta H = 0$ if B ≤ 1ppm, 0.03 if B = 2ppm, 0.06 if B = 3ppm, 0.09 if B ≥ 4ppm	CE _m factor for Boron
Yurioka et al. ⁵⁴	1987	$CE_{by} = C + Mn/3.6 + Cu/20 + Ni/9 + Cr/5 + Mo/4$	For t _{8/5by} time for bainite
Yurioka et al. ⁵⁴	1987	$CE_{fpy} = C + Si/24 + Mn/5 + Cu/10 + Ni/18 + Cr/5 + Mo/2.5 + V/5 + Nb/3$	For HV _{by} and HV _{fpy}
Yurioka et al. ⁵⁴	1987	$CE_{fpy} = C + 0.28 * Mn + 0.053 * Ni + 0.36 * Cr + 0.42 * Mo$	For ferrite-pearlite
AWS ²⁶	2010	$CE_{aws} = C + Mn/4 + Ni/20 + (Cr + V)/10 + Cu/40 + Mo/50$	C-Mn with higher C

Waste Material to New Alloy



Waste material from ARL



Sorting & Blending



Melting & Pouring



Characterization



Tensile bars machining

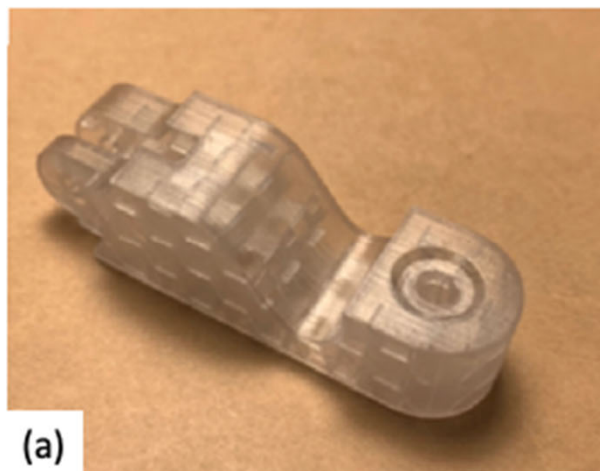
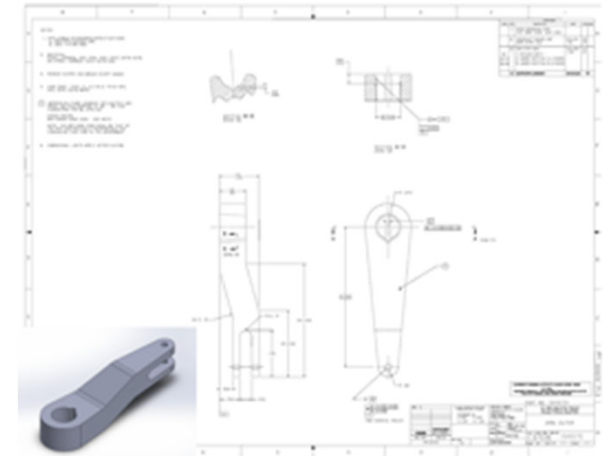
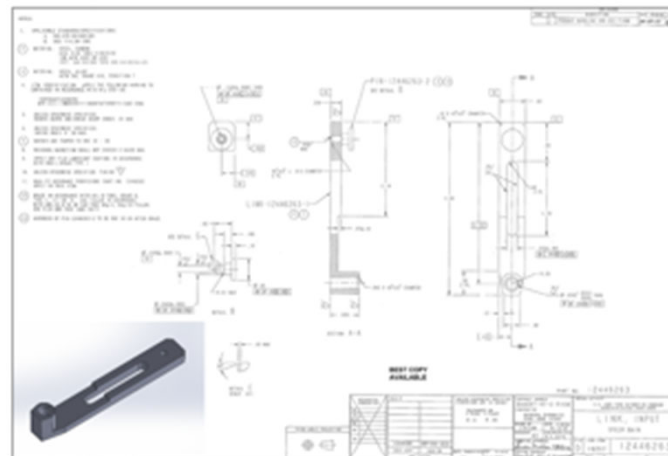
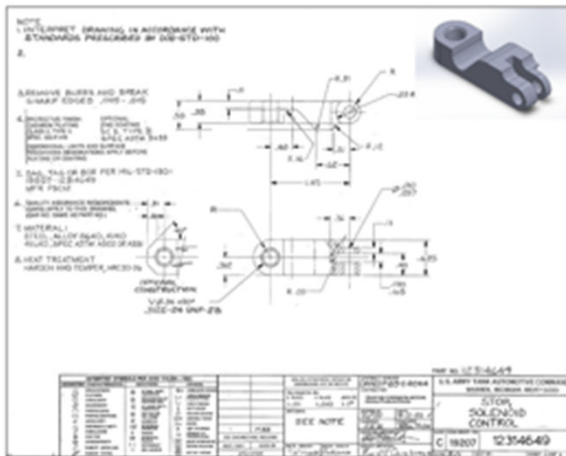


As-cast ingots

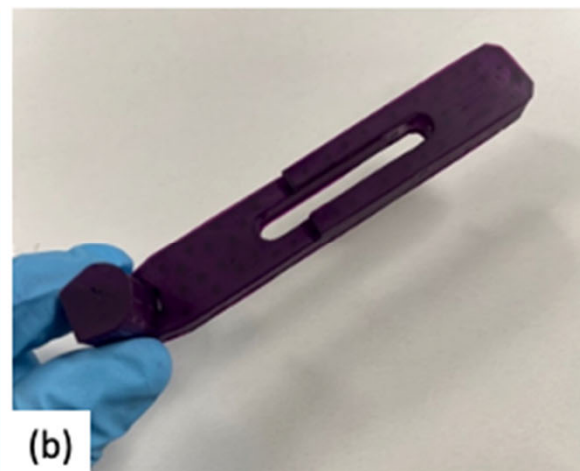
Chemical Composition

		C	Mn	Si	Cr	Mo	Ni	S	P	DI	CE
Part #12314649 Target composition	4140	0.38-0.43	0.75-1.0	0.15-0.3	0.8-1.1	0.15-0.25	/	0-0.04	0-0.0035		
										4.44-8.38	0.64-0.87
	8640	0.38-0.43	0.75-1.0	0.15-0.35	0.4-0.6	0.15-0.25	0.4-0.7	0-0.04	0-0.0035		
Product		0.41	0.805	0.15	1.12	0.215	0.53	0.039	0.023	8.26	0.85
Part #12446263 Target composition	4130	0.28-0.33	0.4-0.6	0.15-0.3	0.8-1.1	0.15-0.25	/	0-0.04	0-0.0035		
	4140	0.38-0.43	0.75-1.0	0.15-0.3	0.8-1.1	0.15-0.25	/	0-0.04	0-0.0035	2.51-6.38	0.54-0.91
	4142	0.4-0.45	0.75-1.1	0.15-0.3	0.8-1.1	0.15-0.25	/	0-0.04	0-0.0035		
	Product		0.29	0.64	0.05	0.87	0.16	0.14	0.03	0.02	2.94
Part #154072 Target composition	1010-1025	0.08-0.28	0.3-0.6	/	/	/	/	0-0.05	0-0.04	0.086-0.45	0.13-0.38
Product		0.176	0.575	0.488	0.127	0.012	0.108	0.03	0.023	0.28	0.27

Direct Fabrication of IC Patterns by SLA



(a)



(b)



(c)

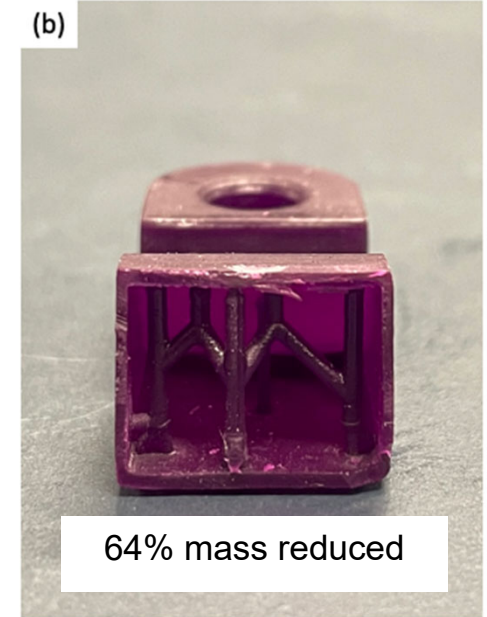
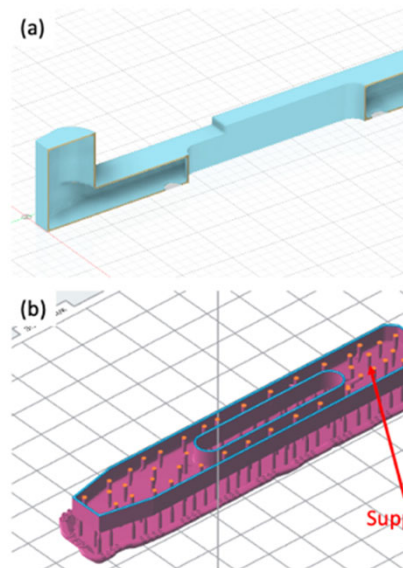
(a) Part #12314649 hollow pattern printed with 3D System Project 600HD; (b) Part#12446263 hollow pattern printed with Formlabs Form 2; (c) Part #154072 hollow pattern printed with Formlabs Form 2.

Direct Fabrication of IC Patterns by SLA

3D System
Projet 6000HD



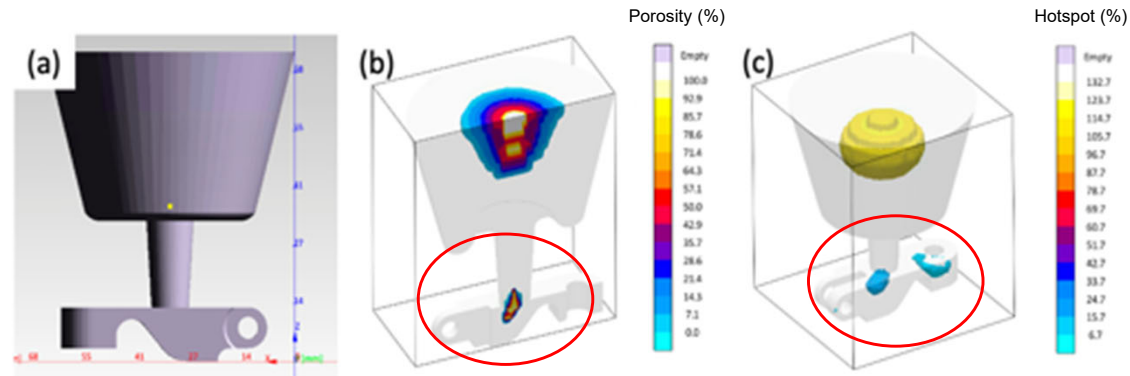
Formlabs
Form 2



64% mass reduced

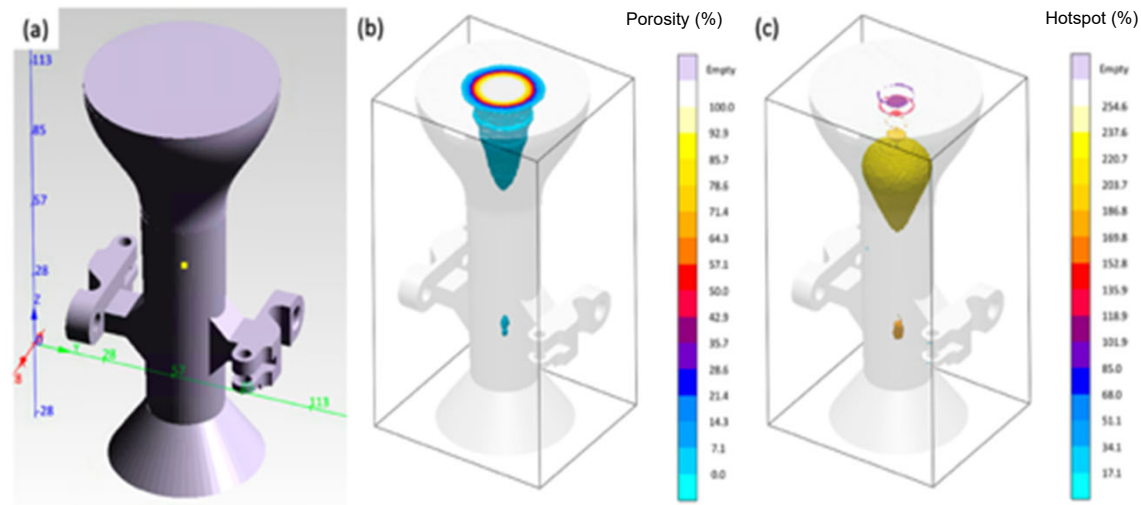
Simulation & Design of Casting Tree

Initial Design:



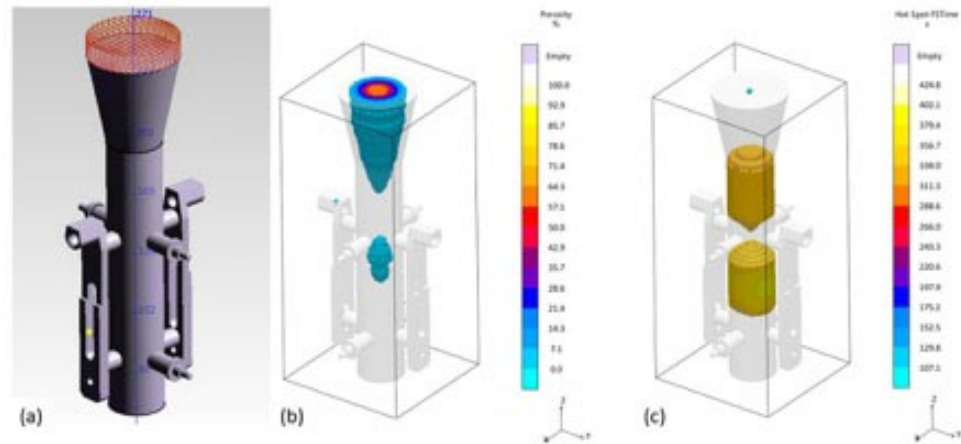
Initial pattern design for Part #12314649. (b) Porosity simulation result and (c) Hot spot simulation result.

Optimized Design:

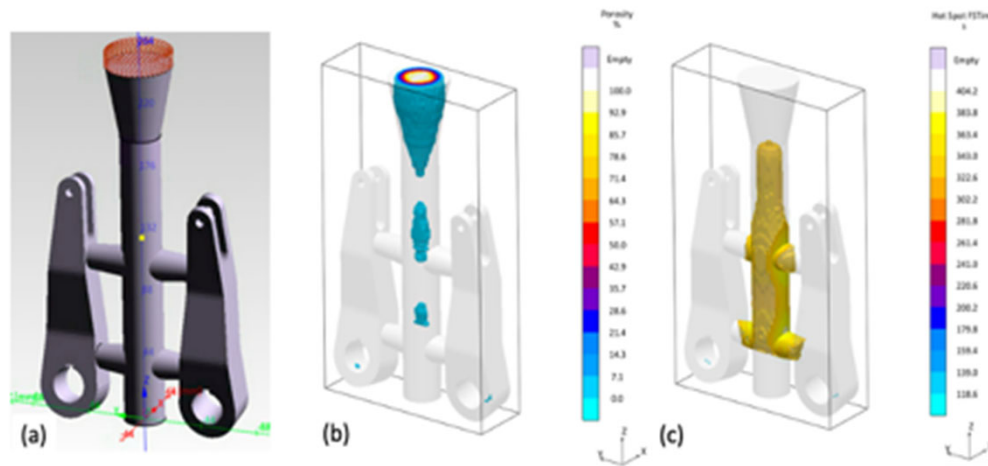


Optimized casting pattern design for Part #12314649. (b) Porosity simulation result and (c) Hot spot simulation result.

Simulation & Design of Casting Tree

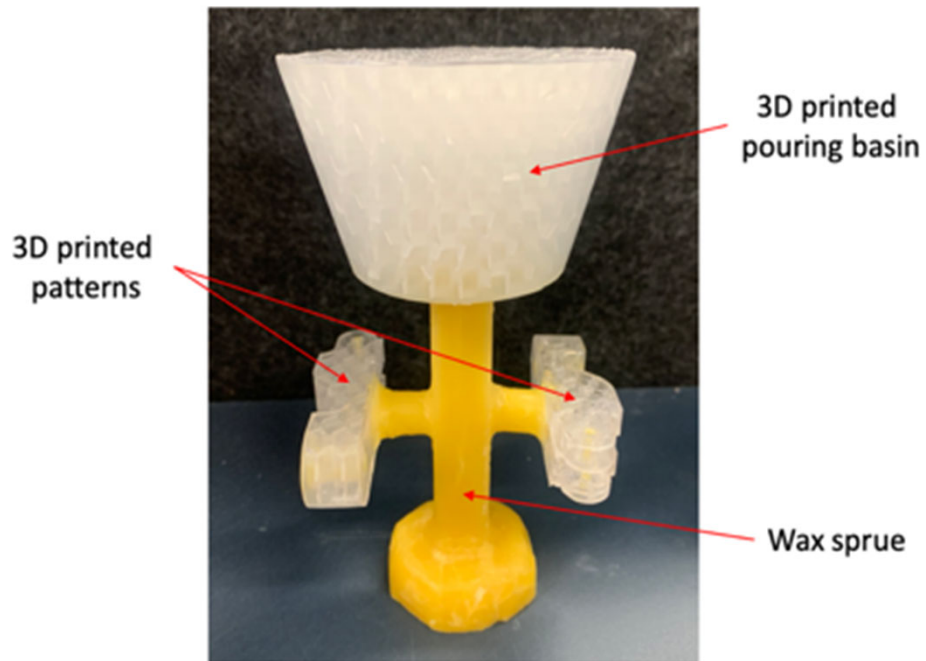


(a) Casting pattern design for Part #12446263; (b) Porosity simulation result; and (c) hot-



(a) Casting pattern design for Part #12446263; (b) Porosity simulation result; and (c) hot-spot simulation result.

Casting Tree Assembly



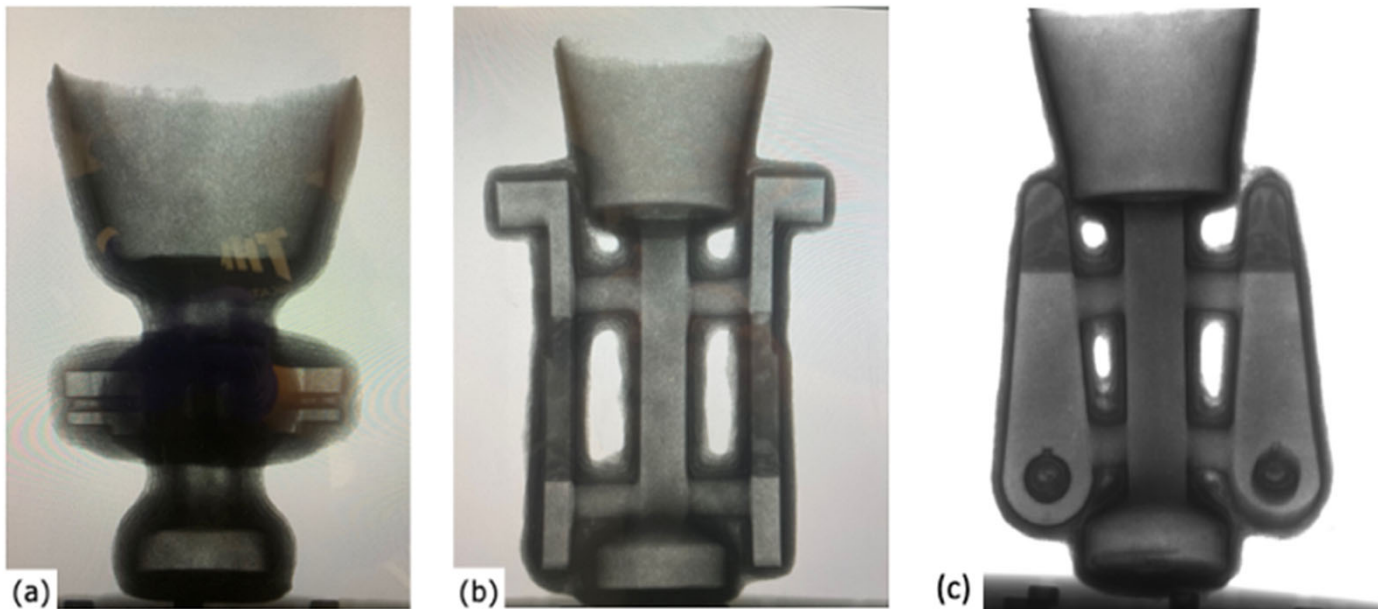
Ceramic Shell after Burnout



Ceramic shells after burnout (a) Part#12314649 casting tree assembly; (b) Part#12446263 casting tree assembly.

Ceramic shell (after burnout) was cut in half to evaluate the internal surface.

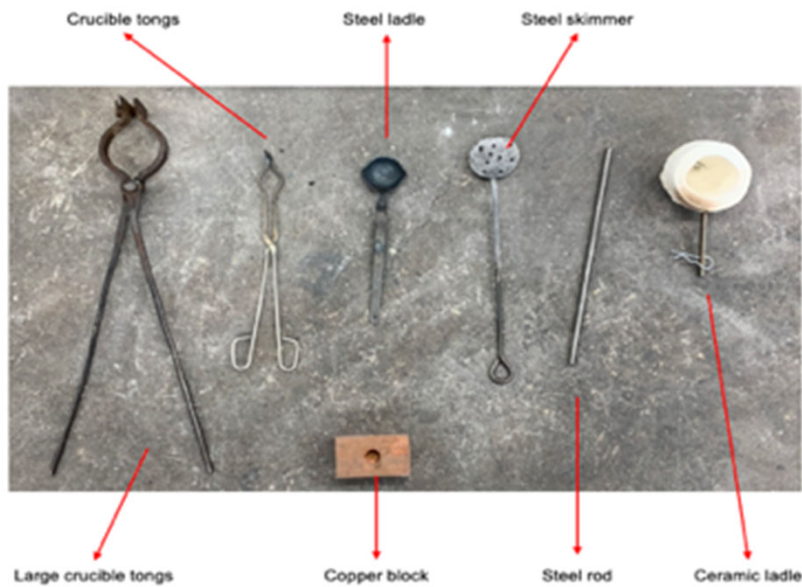
Ceramic Shell Inspection



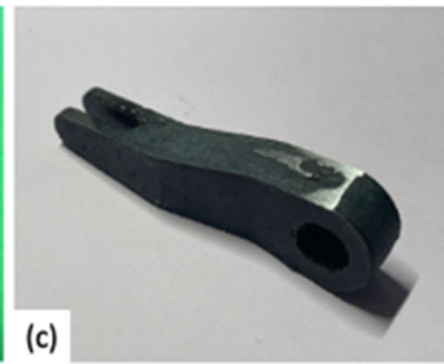
CT scan results of ceramic shells after burnout: (a) Part#12314649 casting tree assembly; (b) Part#12446263 casting tree assembly; (c) Part#154072 casting tree assembly.

Casting Process

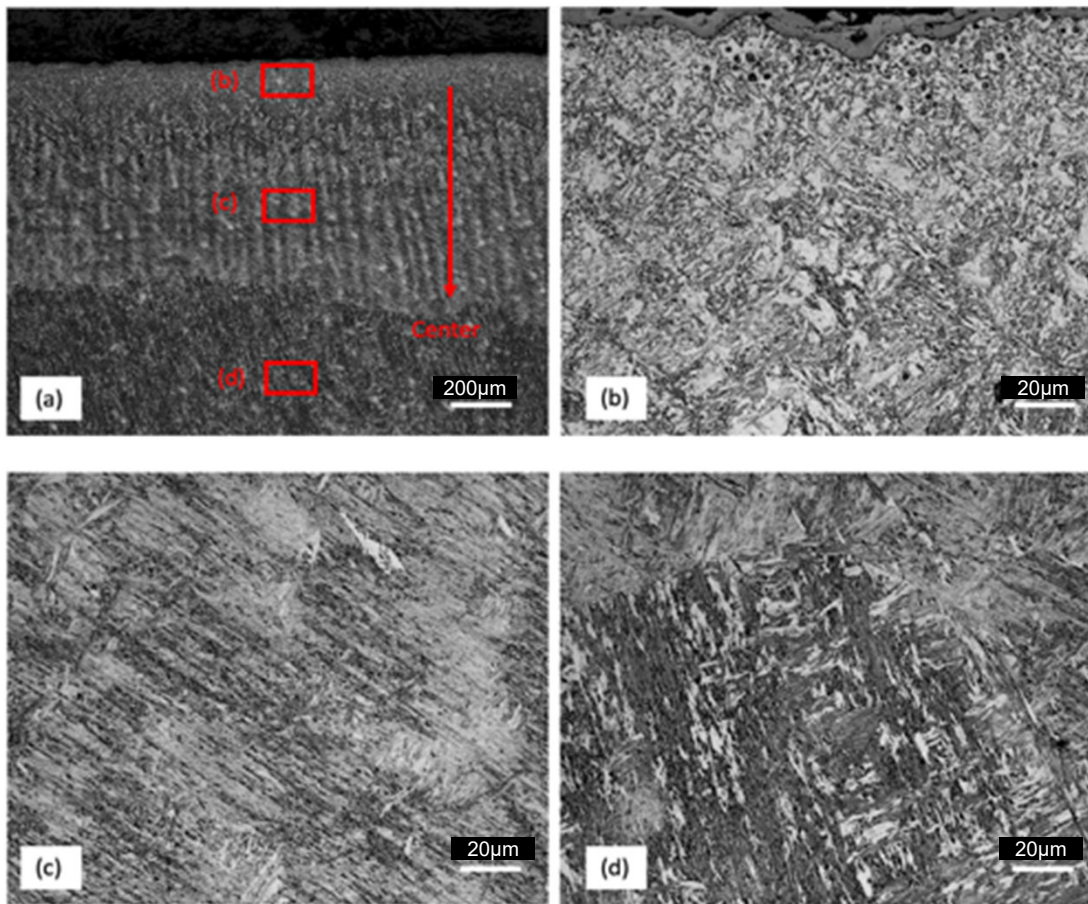
Time (Minutes)	Power (kW)	Action
0	0	Add waste material into crucible
0-30	17	Crucible preheat
30-90	30	Main melting stage
90-110	25	Conduct composition analysis, adjust composition
110-140	30	Temperature measuring, pouring



Post Casting Process

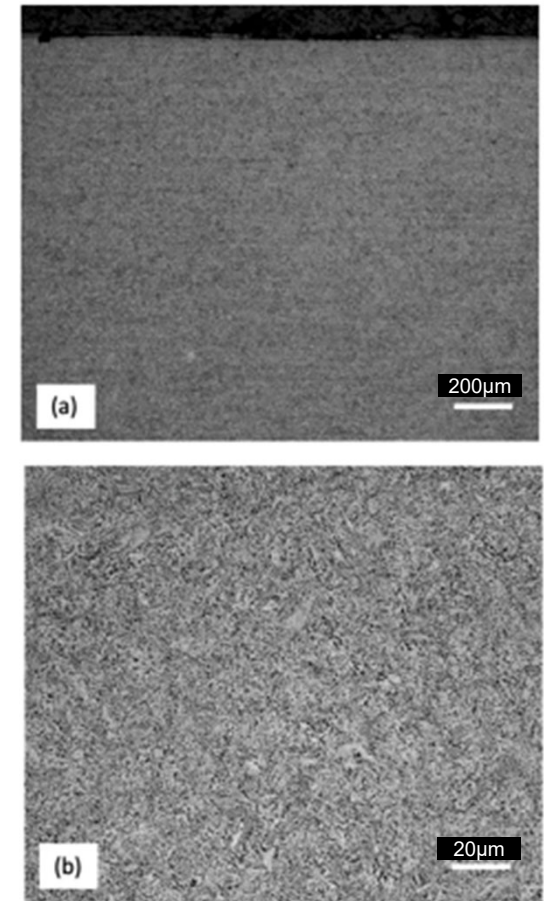


Heat Treatment



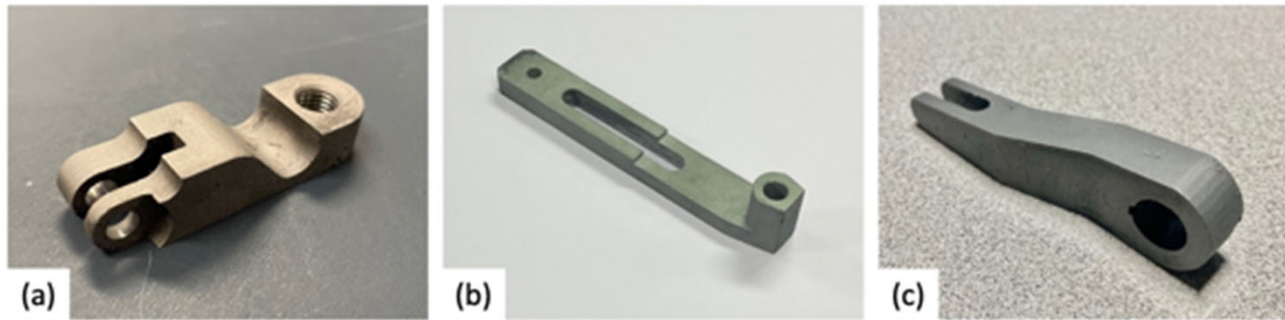
(a) As-cast steel microstructure image, (b) chill zone (c) outer region, (d) transition region.

Heat treatment

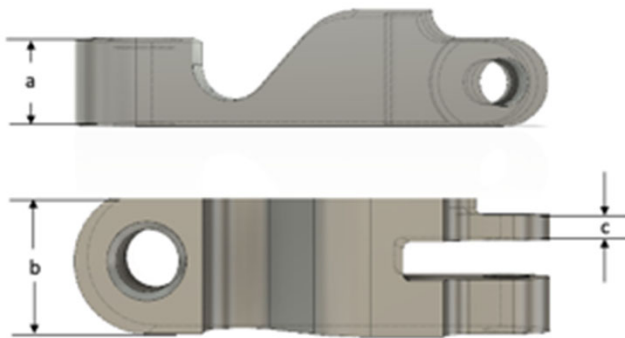


Microstructure after normalizing. (865C, 1hr)

Final Product

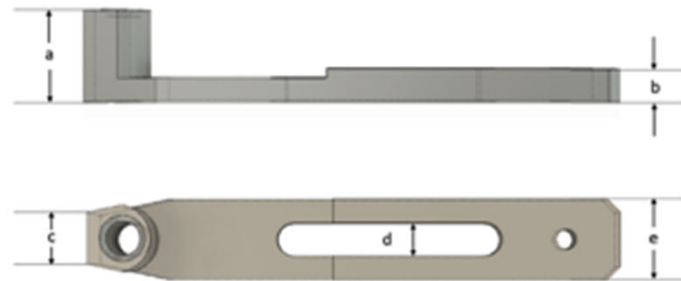


Final parts (a) Part#12314649; (b) Part#12446263; (c) Part#154072.



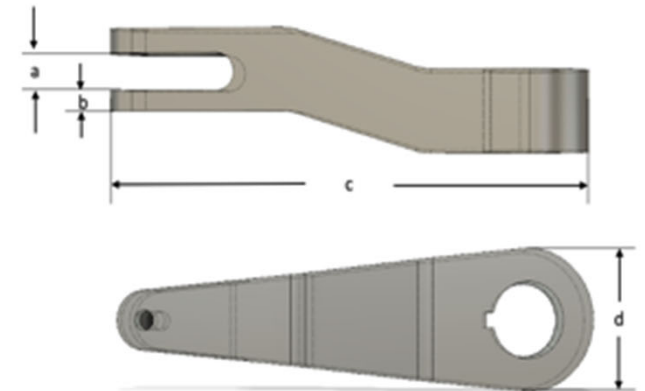
Dimension (in.)	a	b	c
Designed value ± tolerance	0.38 ± 0.01	0.63 ± 0.01	0.11 ± 0.01
3D printed pattern	0.415	0.649	0.113
Cast part	0.371	0.630	0.112

Hardness: 33 HRC



Dimension (in.)	a	b	c	d	e
Design value ± tolerance	0.69±0.03	0.25±0.03	0.38±0.03	0.252±0.03	0.62±0.01
3D printed pattern	0.78	0.32	0.39	0.26	0.64
Cast part	0.698	0.269	0.382	0.257	0.625

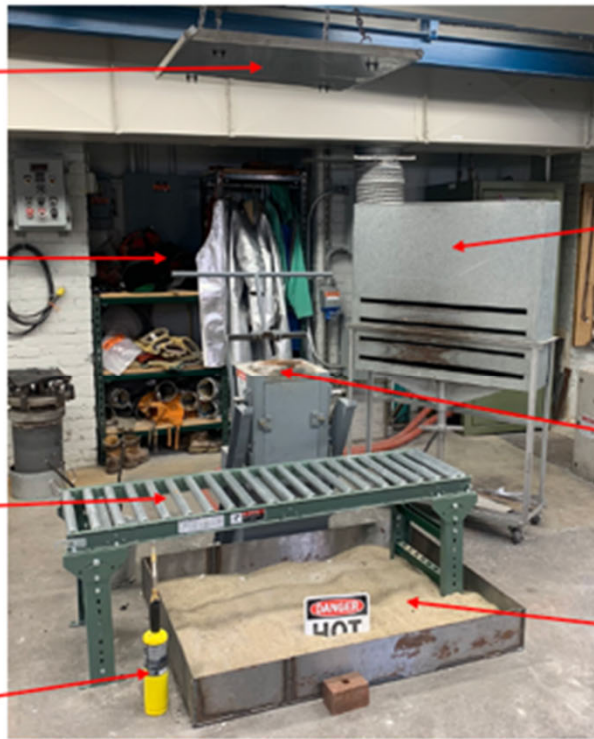
Hardness: 36 HRC



Dimension (in.)	a	b	c	d
Designed value ± tolerance	0.225 ± 0.015	0.125 ± 0.015	3.25 ± 0.015	0.875 ± 0.015
3D printed pattern	0.232	0.129	3.347	0.903
Cast part	0.224	0.128	0.324	0.869

Hardness: 32 HRC

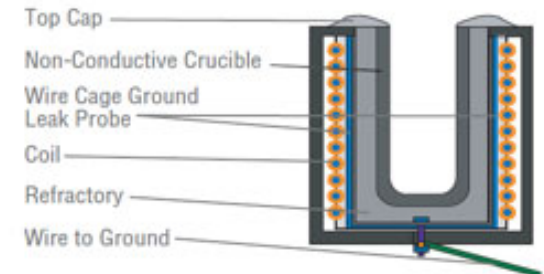
Compact Steel Casting System



Compact foundry system in WPI Washburn Shop.



Mini-Melt furnace as built.



Schematic of induction furnace.

Ceiling protection plate

Personal protective equipment

Roller conveyor

Propane blowtorch

Ventilating fan

Furnace/crucible

Sandpit

Microgrid Power System

The BoxPower SolarContainer is a pre-wired microgrid solution with integrated solar array, battery storage, intelligent inverters, and an optional backup generator. Microgrid system sizes range from 8.5 kW to 50 kW of PV per 20-foot shipping container, which can cover the typical power demand of 45kW by of the mobile foundry system.



- Scalable and replicable microgrid designs
- Off-grid and grid-tied functionality
- Installs in a few hours, minimal foundation requirements
- Pre-wired outlets for plug-and-play use
- Proven effectiveness in extreme weather conditions
- Permit-ready for permanent or temporary use
- Pre-tested in BoxPower's facility before shipping
- Fully automated with remote monitoring and control

Mobile Foundry Design

- A mobile foundry consisting of three standard shipping containers was designed.
- A 3D model of the mobile foundry containers was created using Fusion 360. This modeling allowed for accurate evaluation of the design and quantification of the degree of safety. The use of SolidWorks assemblies provided a helpful visualization of the equipment arrangement in the containers and allowed for a timely alternative for assessing the design and safety efficacy of the mobile foundry.
- Simulations were conducted using ANSYS to ensure safe environment of operation within the designed mobile foundry.
- A list of commercially available equipment and corresponding suppliers for the mobile foundry was created based on extensive research.

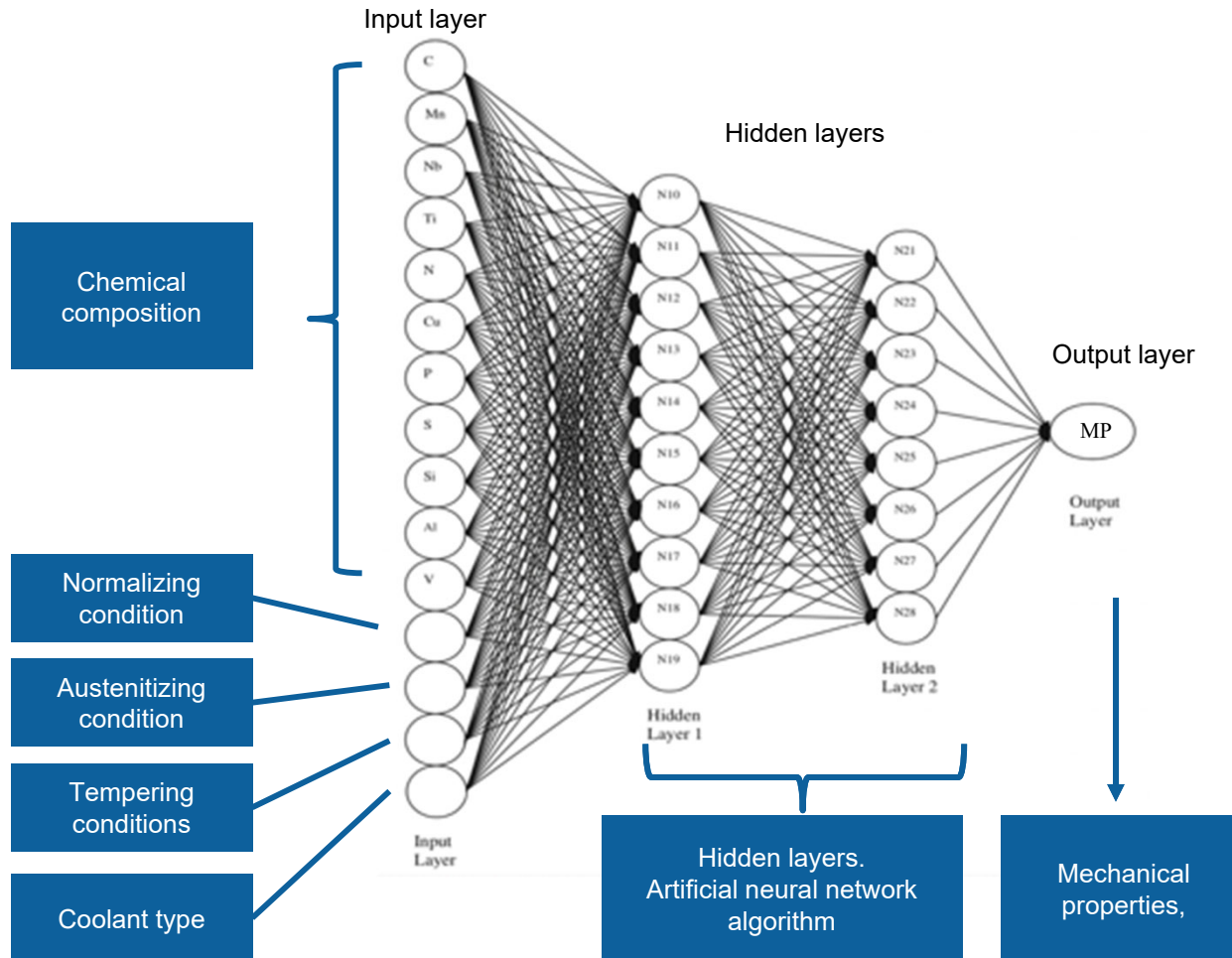
SFSA Data

HT Code	HT statement	Normalize, F	Normalize, hr	N-coolant	tustenitize	stenitize, A-coolant												
QT	air quench, and temper 1100 °F min. ASTM Previous Designation is 4Q																	
NOQT	HR, OIL QUENCH. TEMPER TC	1750	1	air	1750	1	oil											
QT	air quench, and temper 1100 °F min. ASTM Previous Designation is 4Q																	
NOQT	TEMPER 2 HOURS MINIMUM TO F	1750	1		1750	1	oil											
NOQT	TENITIZE 1750 1HR, OIL QUE	1750	1	air	1750	1	oil											
NOQT	HR, OIL QUENCH. TEMPER TC	1750	1	air	1750	1	oil											
QT	JST 1750 1HR, QUENCH. TEF	1750	1		1750	1												
QT	JST 1750 1HR, QUENCH. TEF	1750	1		1750	1												
NOQT	IZE 1750 1HR, OIL QUENCH.	1750	1	air	1750	1	oil											
NOQT	IZE 1750 1HR, OIL QUENCH.	1750	1	air	1750	1	oil											
NOQT	TENITIZE 1750 1HR, OIL QUE	1750	1	air	1750	1	oil											
NOQT	IZE 1750 1HR, OIL QUENCH.	1750	1	air	1750	1	oil											
QT	air quench, and temper 1100 °F min. ASTM Previous Designation is 4Q																	
QT	air quench, and temper 1100 °F min. ASTM Previous Designation is 4Q																	
NOQT	HR, OIL QUENCH. TEMPER TC	1750	1	air	1750	1	oil											
NOQT	TENITIZE 1750 1HR, OIL QUE	1750	1	air	1750	1	oil											
QT	air quench, and temper 1100 °F min. ASTM Previous Designation is 4Q																	
NOQT	IZE 1750 1HR, OIL QUENCH.	1750	1	air	1750	1	oil											
NOQT	TENITIZE 1750 1HR, OIL QUE	1750	1	air	1750	1	oil											
QT	air quench, and temper 1100 °F min. ASTM Previous Designation is 4Q																	
QT	JST 1750 1HR, QUENCH. TEF	1750	1		1750	1												
QT	JST 1750 1HR, QUENCH. TEF	1750	1		1750	1												
QT	JST 1750 1HR, QUENCH. TEF	1750	1		1750	1												
NOQT	TENITIZE 1750 1HR, OIL QUE	1750	1	air	1750	1	oil											
NOQT	TENITIZE 1750 1HR, OIL QUE	1750	1	air	1750	1	oil											
QT	JST 1750 1HR, QUENCH. TEF	1750	1		1750	1												
QT	JST 1750 1HR, QUENCH. TEF	1750	1		1750	1												
NOQT	IZE 1750 1HR, OIL QUENCH.	1750	1	air	1750	1	oil											

HT Code	BHN	UTS, ksi	YS, ksi	%EI	%RA	YS/UTS	UTS/YS	Quality Index
207	105	86	20	47	0.82	1.22	300.52	
207	103	87	17	38	0.85	1.17	287.17	
207	107	88	23	44	0.82	1.22	311.10	
207	110	93	21	57	0.84	1.18	308.18	
207	111	94	20	59	0.85	1.18	306.25	
207	110	95	18	36	0.87	1.16	297.82	
207	110	95	18	36	0.87	1.16	297.82	
203	100	82	20	50	0.82	1.23	295.42	
201	108	85	25	47	0.79	1.27	317.88	
201	110	87	26	37	0.79	1.26	322.25	
201	112	97	25	59	0.87	1.15	321.69	
197	108	81	23	48	0.75	1.33	311.98	
197	106	94	22	44	0.88	1.13	307.71	
179	106	87	23	62	0.82	1.22	310.68	
179	107	88	20	44	0.83	1.21	301.83	
174	125	114	18	40	0.91	1.10	313.13	
171	101	80	21	47	0.79	1.27	299.59	
141	122	107	17	53	0.88	1.14	306.55	
	80	57	22	47	0.71	1.40	281.76	
	95	69	19	40	0.72	1.39	287.23	
	97	71	19	48	0.74	1.35	288.34	
	93	74	18	40	0.79	1.26	281.55	
	95	75	26	68	0.78	1.28	307.25	
	106	75	24	56	0.71	1.41	313.29	
	106	75	24	56	0.71	1.41	313.29	
	95	75	22	51	0.79	1.26	296.37	
	94	76	18	43	0.81	1.24	281.86	
	94	76	18	43	0.81	1.24	281.86	
	107	76	17	38	0.71	1.42	291.88	
	107	76	17	38	0.71	1.42	291.88	
	97	76	21	65	0.78	1.28	295.71	
	102	76	25	58	0.75	1.33	311.49	
	97	77	25	71	0.79	1.26	306.19	

- Chemical composition
- Mechanical properties
- Heat treatment history

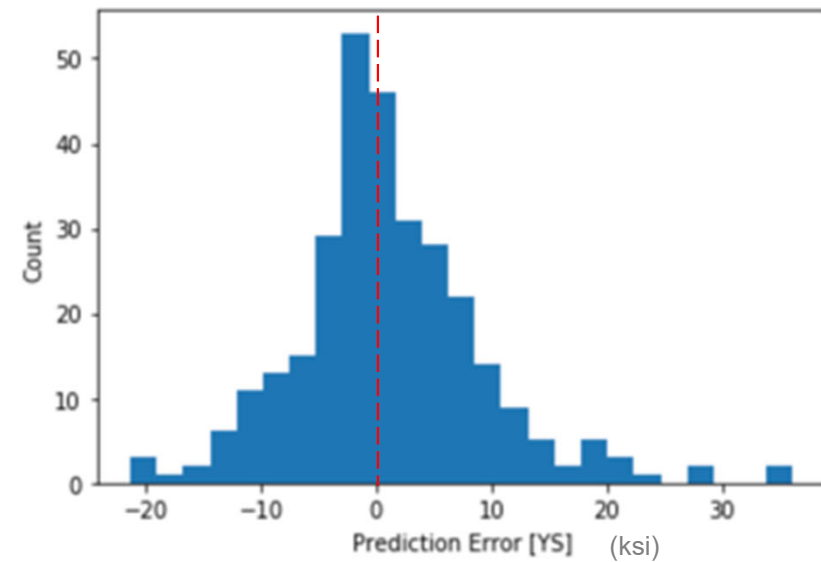
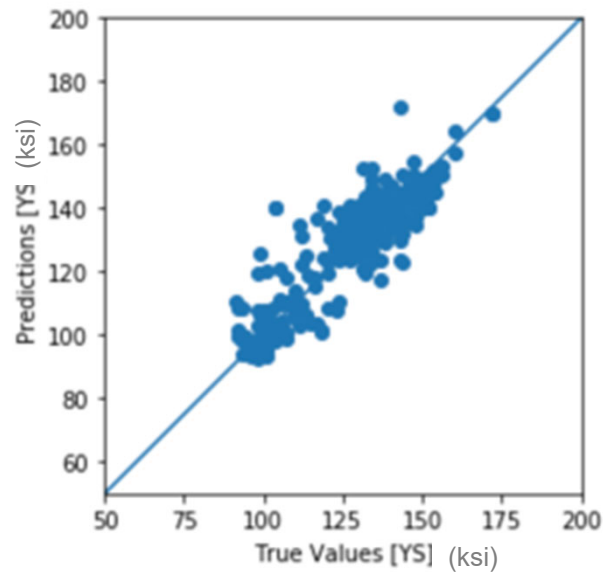
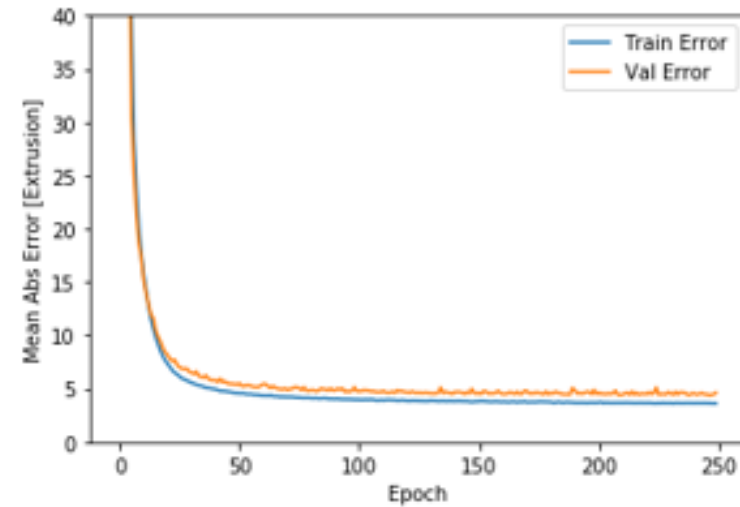
Artificial Neural Networks for Mechanical Properties Prediction



Prediction Result -- YS

YS (Yield Strength)

- Prediction accuracy: 95.57%.
- Standard error of estimate: 5.38 ksi



Prediction Results

Steel grade	Prediction accuracy (%)				Mean error of prediction			
	UTS	YS	BHN	EL	UTS (ksi)	YS(ksi)	BHN	EL(%)
86XX normalized	93.3	86.73	95.23	88.64	6.02	10.33	11.09	2.1
86XX quenched	96.78	95.57	96.3	91.81	4.11	5.38	9.55	1.36
43XX normalized	91.23	86.93	94.3	94.11	10.43	11.52	13.98	0.88
43XX quenched	92.83	92.15	95.24	86.44	9.85	8.4	10.72	1.71
Carbon steel normalized	96.95	94.36	95	93.4	2.25	4.25	8.43	2.1
Carbon steel quenched	94.28	88.91	95.37	91.55	4.6	5.65	7.43	2.38

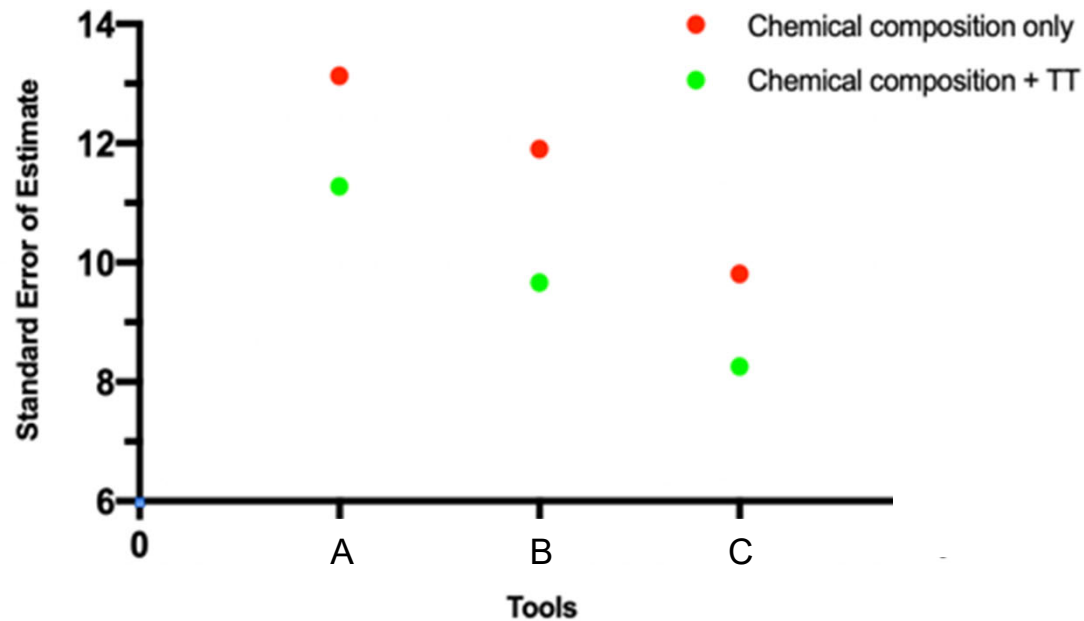
$$\text{Prediction Accuracy} = \frac{1}{N} \sum_{i=1}^N \left(\frac{|Y_i - Y_p|}{Y_i} \right) \times 100\%$$

$$\text{RMSE} = \sqrt{\left(\frac{1}{N} \sum_{i=1}^N (Y_i - Y_p)^2 \right)}$$

Where

Y_i – actual value for Y
 Y_p – predicted value for Y

Prediction Results Comparison



Tool	Chemical Composition only	Chemical Composition +TT
A: Linear regression using ASTM DI A255	13.13 ksi	11.28 ksi
B: Linear regression using Carbon Equivalent CE_{IIW}	11.9 ksi	9.66 ksi
C: ANN model	9.81 ksi	8.26 ksi

Future Work

- Modify a shipping container to be connected to the required power and water supply.
- Create the demo mobile foundry system.
- Demonstrate the production of useful parts by the mobile foundry.
- Developing an environmentally friendly method to deal with the shell materials. (Green recipe using recycled shell powder and sand, ceramic shell waste classification and refinement...)
- Investigating the physical understanding of machine learning model when applying it in metallurgy. Combine current heat treatment software with developed ML models for better heat treatment design.

Technology Transfer

- An Operational Protocol was created.
- 14 Students and post-doctoral researchers have been trained through this project and are currently working in relevant industry and research institutes.
- Presentations and publications at professional conferences and in professional journals.
- Media coverage.

Students and Postdocs

- Three Post-Docs: currently at Phoenix Motorcars in CA, Mattson Technology, Inc. in CA, and Yale University in CT
- Two PhD dissertations: currently at Mattson Technology, Inc. in CA and the Steel Founders' Society of America.
- One Master student: currently at Hitchiner Manufacturing in NH
- Three undergraduate projects with eight students. One project was presented at the ASEE NE 2021, IEEE MIT Undergraduate Research Conference 2021 and Sigma Xi Student Research Conference 2021. Title: "Outfitting a Compact Steel Casting System for Mobile Foundry for Department of Defense (DoD) Rapid Equipping Force (REF)"

Papers and Conferences

1. Varde, Aparna & Liang, Jianyu. (2023). Machine Learning Approaches in Agile Manufacturing with Recycled Materials for Sustainability. AAAI 2023, the 37th AAAI Conference on Artificial Intelligence (Bridge Program). Washington, DC. Volume: AI for Materials Science (AIMAT)
2. Yutao Wang, Jianyu Liang, Diran Apelian, Brajendra Mishra, Richard Sisson, Jian Yu, Brandon McWilliams. From Waste Steel to Material: Agile production enabled by additive manufacturing. SERDP and ESTPC Symposium. Dec. 2022
3. Wang W, Yang Z, Ge X, Sisson RD, Mishra B, Varde A, Liang J, Machine learning tools to predict mechanical properties of steel alloys based on compositions, heat treatments and microstructures, MS&T, Columbus, Ohio. Oct. 2021.
4. Wang W, Yang Z, Ge X, Sisson RD, Mishra B, Varde A, Liang J. Machine learning tools to predict mechanical properties of steel alloys based on compositions, heat treatments and microstructures, 2021 DoD Steels Research Summit, Nov. 2021 (virtual).
5. Wang W, Yang Z, Sisson RD, Mishra B, Apelian D, Liang J. From Waste Steel to Matériel: Additive Manufacturing Enabled Agile Manufacturing. SERDP Symposium. Dec. 2021 (virtual)
6. The undergraduate project as part of this project was presented at the ASEE NE 2021, IEEE MIT Undergraduate Research Conference 2021 and Sigma Xi Student Research Conference 2021. Title: "Outfitting a Compact Steel Casting System for Mobile Foundry for Department of Defense (DoD) Rapid Equipping Force (REF)"
7. Raymond Monroe and Jianyu Liang. Predicting Cast Steel Alloy Properties Based on Composition and Heat Treatment. Steel Founders' Society of America. The National Technical & Operating (T&O) Conference, Dec. 2020.
8. Karl Sundberg, Raymond Monroe, Yutao Wang, Jianyu Liang, Diran Apelian, Richard Sisson, Brajendra Mishra, Jian Yu, Brandon McWilliams, From Waste Steel to Material: Agile Production Enabled by Additive Manufacturing, Scrap Supplements and Alternative Ironmaking. March 2020. Orlando, USA
9. Yutao Wang, Karl Sundberg, Jianyu Liang, Diran Apelian, Brajendra Mishra, Richard Sisson, Jian Yu, Brandon McWilliams. From Waste Steel to Material: Agile production enabled by additive manufacturing. SERDP and ESTPC Symposium. Dec. 2020
10. Jianyu Liang, Richard Sisson and Raymond Monroe. Machine learning to understand and design heat-treatment process based on steel alloy composition. DoD Steel Summit, Dec. 2020.
11. Sundberg, K., Kelly, S., Mishra, B., Apelian, D., Sisson, R., and Liang, J. (March 2019). From Waste Steel to Matériel: Additive Manufacturing Enabled Agile Manufacturing. Symposium on Recycling, Waste Treatment and Clean Technology (REWAS 2019), San Antonio, TX. (Invited)
12. Wang, Y., Sundberg, K., Mishra, B., Apelian, D., Sisson, R., Liang, J., McWilliams, B. (October 2019). From Waste Steel to Matériel: Additive Manufacturing Enabled Agile Manufacturing. MS&T 2019, Portland, OR.
13. Wang, Y., Sundberg, K., Mishra, B Apelian, D., Sisson, R., Liang, J. and McWilliams, B. (November 2019). From Waste Steel to Matériel: Additive Manufacturing Enabled Agile Manufacturing. DoD Steel Summit, APG, Aberdeen, MD.
14. Sundberg, K., Monroe, R., Wang, Y., Liang, J., Apelian, D., Sisson, R., Mishra, B., Yu, J., McWilliams, B. (December 2019). From Waste Steel to Matériel: Additive Manufacturing Enabled Agile Manufacturing. The Strategic Environmental Research and Development Program(SERDP) and the Environmental Security Technology Certification Program (ESTCP) Symposium, Washington DC.
15. Sundberg, K., Kelly, S., Apelian, D., Sisson, R., and Liang, J. (November 2018). "From Waste Steel to Weapons: Agile Production Enabled by Additive Manufacturing," 2018 Strategic Environmental Research and Development Program and Environmental Security Technology Certification Program (SERDP and ESTCP) Symposium, Washington DC.
16. Sundberg, K., Kelly, S., Apelian, D., Sisson, R., and Liang, J. (March 2019). "From Waste Steel to Weapons: Agile Production Enabled by Additive Manufacturing," Symposium on Recycling, Waste Treatment and Clean Technology

Project Featured in Media

- Innovation Couldn't Wait: How Research Rolled On: WPI Researchers Found Creative Ways to Keep Their Projects Moving Ahead, special Summer issue of the WPI Journal 2021: [Weblink](#)
- SEDRP Project on WPI Website: [Weblink](#)
- Modern Casting, June 2021: [Weblink](#)



Key Points

- Created an effective sorting, chemical composition monitoring and composition adjustment process for ferrous wastes at FOBs that enables quality control of remelted material.
- Established an additive manufacturing (AM) technology of stereo lithography apparatus (SLA) enabled investment casting (IC) process using ferrous wastes from FOBs as the cast material.
- Designed a compact and safe mobile foundry system and conducted technology transfer study.
- Developed machine learning models to study the relationship between mechanical properties, microstructure, and chemical composition of cast steel products.
- Developed model shows higher prediction accuracy than traditional linear regression model.

BACKUP SLIDES

WP18-1176: From Waste Steel to Matériel: Additive Manufacturing Enabled Agile Manufacturing

Performers: WPI, ARL and ERCo

Technology Focus

- Creating a 3D printing enabled investment casting process using iron wastes generated at FOBs

Research Objectives

1. Creating an effective sorting, chemical composition monitoring and composition adjustment process for iron wastes at FOBs
2. Establishing additive manufacturing (AM) technology enabled investment casting (IC) using iron wastes from FOBs as the cast material
3. Optimizing and minimizing post process treatments

Project Progress and Results

- Created an effective sorting, chemical composition monitoring and composition adjustment process Established an additive manufacturing (AM) enabled investment casting (IC) process using ferrous wastes from FOBs as the cast material.
- Designed a compact and safe mobile foundry system and conducted technology transfer study.
- Developed machine learning models to study the relationship between mechanical properties, microstructure, and chemical composition of cast steel products.
- Developed model shows higher prediction accuracy than traditional linear regression model.

Technology Transition

- ESTCP
- Defense University Research Instrumentation Program

